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Monterey, California. Naval Postgraduate School

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## THESIS

OPTIMIZATION OF SURFACE SHIP STEERING  
IN SEA STATE

by

Emmanuel Horianopoulos

December 1984

Thesis Advisor:

George J. Thaler

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|---|-----------------------|--|
| 1. REPORT NUMBER  | 2. GOVT ACCESSION NO. | 3. RECIPIENT'S CATALOG NUMBER  |
| 4. TITLE (and Subtitle)<br>Optimization of Surface Ship Steering<br>in Sea State  |                       | 5. TYPE OF REPORT & PERIOD COVERED<br>Master's Thesis<br>December 1984 |
|   |                       | 6. PERFORMING ORG. REPORT NUMBER                                       |
| 7. AUTHOR(s)<br>Emmanuel Horianopoulos  |                       | 8. CONTRACT OR GRANT NUMBER(s)   |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>Naval Postgraduate School<br>Monterey, California 93943  |                       | 10. PROGRAM ELEMENT, PROJECT, TASK<br>AREA & WORK UNIT NUMBERS         |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>Naval Postgraduate School<br>Monterey, California 93943  |                       | 12. REPORT DATE<br>December 1984                                       |
|   |                       | 13. NUMBER OF PAGES<br>116   |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)<br>Naval Postgraduate School<br>Monterey, California 93943  |                       | 15. SECURITY CLASS. (of this report)<br>Unclassified                   |
|   |                       | 15a. DECLASSIFICATION/DOWNGRADING<br>SCHEDULE                          |
| 16. DISTRIBUTION STATEMENT (of this Report)<br><br>Approved for public release; distribution is unlimited   |                       |  |
| 17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)  |                       |  |
| 18. SUPPLEMENTARY NOTES   |                       |  |
| 19. KEY WORDS (Continue on reverse side if necessary and identify by block number)<br>Computer models of the ship, Nomoto model, Regular seas,<br>Optimized controller, Irregular seas, Minimization subroutine,<br>Adaptive control  |                       |  |
| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br><br>Propulsion losses are increased by added drag due to<br>steering of the ship. A carefully designed automatic steering<br>control provides the desired heading while it simultaneously<br>minimizes the rudder activity and holds the potential for re-<br>ducing propulsive losses.<br>A computer model of the SJ-7 containership along with a<br>cascaded controller (one pole, one zero) were coupled to a |                       |  |



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The model was tested in calm waters and sea states (regular and irregular) as well, for a certain speed and different encounter wave angles and encounter frequencies.

Also, an adaptive control was studied which updates the controller parameters while either the environmental conditions or the ship's steering characteristics change in order to maintain optimal steering performance.

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Optimization of Surface Ship Steering  
in Sea State

by

Emmanuel Horianopoulos  
Lieutenant, Hellenic Navy  
B.S., Naval Academy of Greece, 1975

Submitted in partial fulfillment of the  
requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING SCIENCE

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# ABSTRACT

Propulsion losses are increased by added drag due to steering of the ship. A carefully designed automatic steering control provides the desired heading while it simultaneously minimizes the rudder activity and holds the potential for reducing propulsive losses.

A computer model of the SL-7 containership along with a cascaded controller (one pole, one zero) were coupled to a function minimization subroutine and a sea state generator program. This scheme provided the appropriate controller parameters in order to accomplish the best performance.

The model was tested in calm waters and sea states (regular and irregular) as well, for a certain speed and different encounter wave angles and encounter frequencies.

Also, an adaptive control was studied which updates the controller parameters while either the environmental conditions or the ship's steering characteristics change in order to maintain optimal steering performance.

# TABLE OF CONTENTS

|       |   |    |
|-------|---|----|
| I.    | INTRODUCTION . . . . .  | 11 |
| II.   | COMPUTER MODELS OF THE SHIP . . . . .                           | 13 |
| III.  | AN ADEQUATE PERFORMANCE CRITERION . . . . .                     | 16 |
|       | A. CRITERION BASED ON TRUE ADDED RESISTANCE . . . . .           | 16 |
|       | B. CRITERION BASED ON APPROXIMATE ADDED<br>RESISTANCE . . . . . | 18 |
|       | C. WEIGHTING FACTOR STUDY . . . . .                             | 19 |
| IV.   | REGULAR SEAS - CONTROLLER DESIGN . . . . .                      | 23 |
| V.    | IRREGULAR SEAS - CONTROLLER DESIGN . . . . .                    | 46 |
| VI.   | MINIMIZATION SUBROUTINE FOR ONBOARD USE . . . . .               | 53 |
|       | A. GENERAL . . . . .  | 53 |
|       | B. ATTACKING THE PROBLEM . . . . .                              | 54 |
|       | C. SOLVING THE PROBLEM . . . . .                                | 54 |
| VII.  | ADAPTIVE CONTROL . . . . .                                      | 57 |
|       | A. NECESSITY OF ADAPTIVITY . . . . .                            | 57 |
|       | B. CANDIDATE ADAPTIVE SCHEMES . . . . .                         | 57 |
| VIII. | CONCLUSIONS AND RECOMMENDATIONS . . . . .                       | 62 |
|       | A. CONCLUSIONS . . . . .  | 62 |
|       | B. RECOMMENDATIONS FOR FUTURE STUDIES . . . . .                 | 63 |
|       | APPENDIX A: NOMOTO THIRD ORDER MODEL DETERMINATION . . . . .    | 65 |
|       | APPENDIX B: REGULAR SEASTATE FORMULATION . . . . .              | 73 |
|       | APPENDIX C: SYSTEM'S RESPONSE FOR REGULAR SEAS . . . . .        | 81 |



|  |     |
|--|-----|
| APPENDIX D: IRREGULAR SEASTATE FORMULATION . . . . .       | 88  |
| APPENDIX E: SYSTEM'S RESPONSE FOR IRREGULAR SEAS . . . . . | 95  |
| APPENDIX F: MODIFIED MINIMIZATION SUBROUTINE . . . . .     | 102 |
| LIST OF REFERENCES . . . . .                               | 114 |
| INITIAL DISTRIBUTION LIST . . . . .                        | 115 |

# LIST OF TABLES

|       |  |    |
|-------|--|----|
| I.    | Weighting factor $\lambda''$ . . . . .                                 | 18 |
| II.   | Weighting factor $\lambda'$ . . . . .                                  | 19 |
| III.  | Weighting factor $\lambda$ . . . . .                                   | 19 |
| IV.   | Sea state vs Wave height . . . . .                                     | 24 |
| V.    | Optimal Controller Parameters for Regular Sea<br>Sea State 4 . . . . . | 27 |
| VI.   | Optimal Controller Parameters for Regular Sea<br>Sea State 6 . . . . . | 28 |
| VII.  | Optimal Controller Parameters for Regular Sea<br>Sea State 7 . . . . . | 29 |
| VIII. | Optimal Controller Parameters for Regular Sea<br>Sea State 9 . . . . . | 30 |
| IX.   | Optimal Controller Parameters for Random Sea . . .                     | 48 |
| X.    | First Modification in BOXPLX . . . . .                                 | 55 |
| XI.   | Second Modification in BOXPLX . . . . .                                | 56 |

## LIST OF FIGURES

|      |  |    |
|------|--|----|
| 2.1  | Controller Optimization Scheme . . . . .   | 14 |
| 2.2  | Nomoto Transfer Functions . . . . .  | 14 |
| 2.3  | Nomoto Model Determination Scheme . . . . .  | 15 |
| 3.1  | Closed Loop Bandwidth for $\lambda=8.128$ . . . . .  | 21 |
| 3.2  | Closed Loop Bandwidth for $\lambda=5.734$ . . . . .  | 22 |
| 4.1  | Controller Used in this Study . . . . .  | 24 |
| 4.2  | Yaw vs Time, Sea State 4. Encounter Frequency<br>1.5 rads per sec, Encounter Angle $120^\circ$ . . . . .       | 31 |
| 4.3  | Rudder vs Time, Sea State 4. Encounter<br>Frequency 1.5 rads per sec, Encounter Angle<br>$120^\circ$ . . . . . | 32 |
| 4.4  | Yaw vs Time, Sea State 6. Encounter Frequency<br>1.5 rads per sec, Encounter Angle $120^\circ$ . . . . .       | 33 |
| 4.5  | Rudder vs Time, Sea State 6. Encounter<br>Frequency 1.5 rads per sec, Encounter Angle<br>$120^\circ$ . . . . . | 34 |
| 4.6  | Yaw vs Time, Sea State 7. Encounter Frequency<br>1.5 rads per sec, Encounter Angle $120^\circ$ . . . . .       | 35 |
| 4.7  | Rudder vs Time, Sea State 7. Encounter<br>Frequency 1.5 rads per sec, Encounter Angle<br>$120^\circ$ . . . . . | 36 |
| 4.8  | Yaw vs Time, Sea State 9. Encounter Frequency<br>1.5 rads per sec, Encounter Angle $120^\circ$ . . . . .       | 37 |
| 4.9  | Rudder vs Time, Sea State 9. Encounter<br>Frequency 1.5 rads per sec, Encounter Angle<br>$120^\circ$ . . . . . | 38 |
| 4.10 | Cost vs $K_1$ , Sea State 4. Encounter frequency 1.5<br>rads per sec, Encounter Angle $120^\circ$ . . . . .    | 39 |

|      |   |    |
|------|---|----|
| 4.11 | Cost vs T1,Sea State 4. Encounter frequency 1.5<br>rads per sec, Encounter Angle 120° . . . . .                 | 40 |
| 4.12 | Cost vs T2,Sea State 4. Encounter frequency 1.5<br>rads per sec, Encounter Angle 120° . . . . .                 | 41 |
| 4.13 | Cost vs T2,Sea State 6. Encounter Frequency 1.5<br>rads per sec, Encounter Angle 120° . . . . .                 | 42 |
| 4.14 | Cost vs T2,Sea State 6. Encounter Frequency 0.6<br>rads per sec, Encounter Angle 90° . . . . .                  | 43 |
| 4.15 | Yaw vs Time.Sea State 4,Frequency 0.4,Angle<br>60°. Filter for Sea State 9,Frequency 1.5,Angle<br>120°. . . . . | 44 |
| 4.16 | Rudder vs Time.Sea 4,Frequency 0.4,Angle 60°.<br>Filter for Sea State 9,Frequency 1.5,Angle<br>120°. . . . .    | 45 |
| 5.1  | Yaw vs Time, Sea state 6. Encounter Angle 60°. . .  | 49 |
| 5.2  | Rudder vs Time, Sea State 6. Encounter Angle<br>60°. . . . .  | 50 |
| 5.3  | Yaw vs Time, Sea State 7. Encounter Angle 60°. . .  | 51 |
| 5.4  | Rudder vs Time, Sea State 7. Encounter Angle<br>60°. . . . .  | 52 |
| 7.1  | Adaptive Control Scheme . . . . .   | 58 |
| 7.2  | On Line Adaptive Scheme . . . . .   | 60 |



## ACKNOWLEDGMENTS

The author would like to express his gratitude to his thesis advisor Dr George J. Thaler for his outstanding and professional guidance during the course of this research.

Special thanks to Lt Vicente Chavez Garcia Jr, USN for his support and Lcdr Jim Cass, USN for providing the sea state generator program.

Finally, the author express his gratitude to his wife Eleni for her patience, encouragement and support throughout this effort.

## I. INTRODUCTION

The economics associated with ship operations have necessitated an examination of the losses associated with the motion of an automatically steered ship in a seaway.

Four major areas where fuel losses occur during the operation of a ship have been identified [Ref. 1, 2]. These areas on existing steam/diesel tankers are shown below:

- Power plant and auxiliaries
- Propeller efficiency
- Hull resistance
- Steering and navigation

An optimized autopilot design would provide effective steering control with associated cost savings due to reducing fuel consumption.

An appropriate computer model which represents the ship is necessary for studies leading to appropriate controller design. Chapter 2 introduces the development of two of these models.

Chapter 3 addresses the formulation of a performance criterion which represents the added drag due to steering of the ship.

Using the equations of motion as a model of the ship and a function minimization subroutine we proceed to the controller design for regular seas (deterministic model for the seaway) in Chapter 4, and for irregular seas (nondeterministic model) in Chapter 5. The function minimization subroutine used was BOXPLX and was programmed by R. R. Hilleary of the Naval Postgraduate School Computer Center [Ref. 3]. It will find the minimum of any arbitrary function, linear or nonlinear, subject to explicit constraints of the variables or implicit constraints on functions of the variables.

Chapter 6 introduces another function minimization subroutine appropriate for onboard use.

An adaptive control, which updates the controller parameters when the environmental conditions or the ship's course change, is studied in Chapter 7.

Conclusions drawn from these experiments and recommendations for future studies are addressed in Chapter 8.

## II. COMPUTER MODELS OF THE SHIP

A nontrivial part of any control problem is modelling the process. Thus, an appropriate computer model which represents the ship is necessary. The best representation of the ship's steering dynamics is a Taylor's series expansion of the force and moment relationships around a selected steady state operating point. The equations obtained in this way are known as the equations of motion [Ref. 4], and the formulation in the computer program is indicated in Appendix A. This computer program was developed by using known available data for the SL-7 containership and by implementation of the scheme in Figure 2.1 [Ref. 5].

In this scheme the function minimization subroutine is fed by the yaw error  $\psi_e$  and rudder angle  $\delta$ , computes the performance criterion  $J$  and adjusts the controller free parameters in order to minimize  $J$ .

A second model for the ship-steering dynamics representation is the Nomoto model. Figure 2.2 indicates the second and third order Nomoto transfer functions while Figure 2.3 indicates the appropriate scheme used for obtaining these models from the equations of motion. Appendix A includes the computer program used for the Nomoto third order model determination.

A yaw command is applied as input in the scheme in Figure 2.3 and the difference of the signals  $\psi_M$  and  $\psi_{EQ}$  is fed to the function minimization subroutine which attempts to adjust the free parameters of the Nomoto plant in order to minimize the performance criterion  $J$ .

Simulation runs indicate that the resulting Nomoto models are obtained with resulting  $J$  close to zero. However, in this study the equations of motion



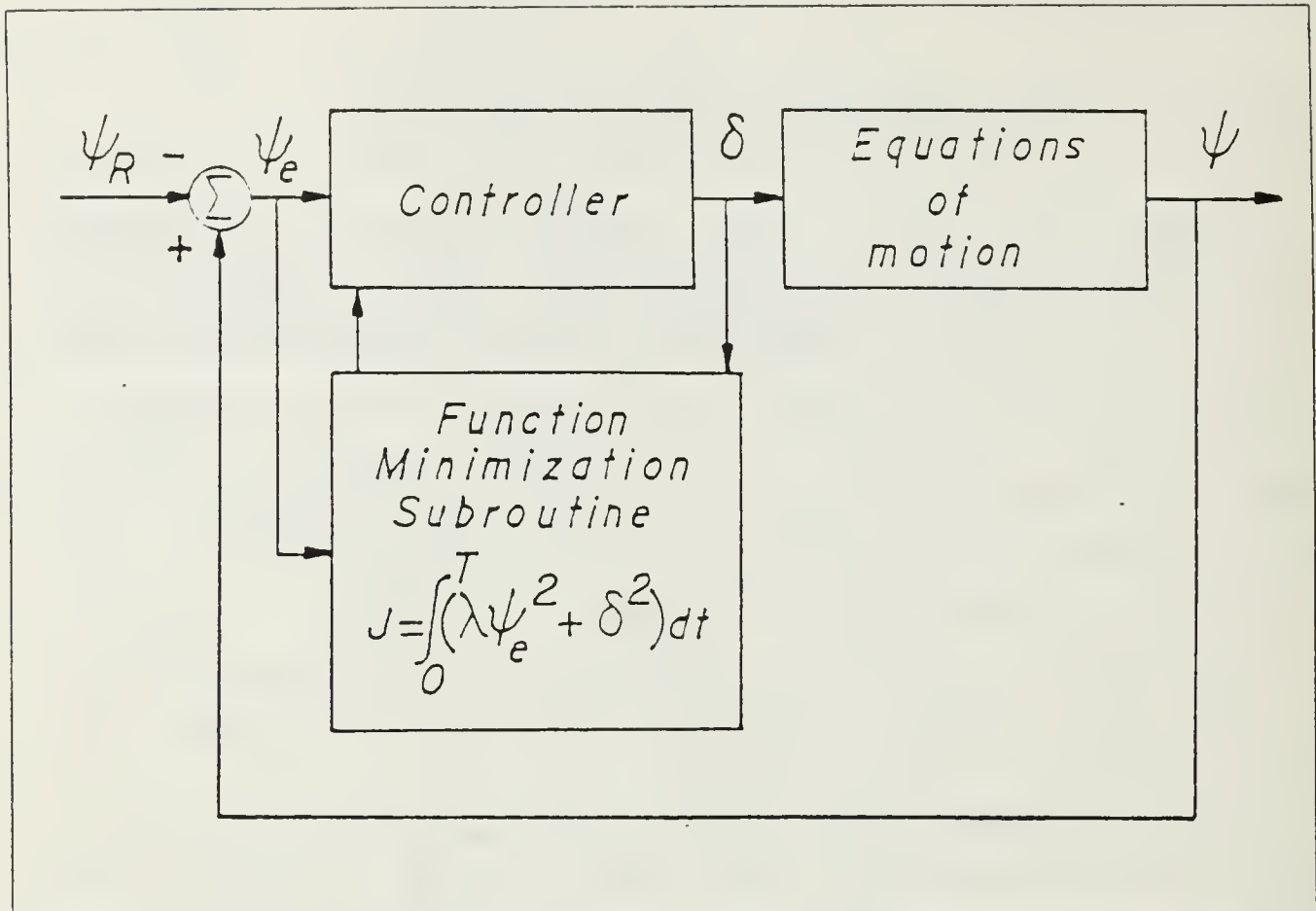


Figure 2.1 . Controller Optimization Scheme

$$\frac{\psi}{\delta} = \frac{K}{s(Ts+1)}$$

Second order

$$\frac{\psi}{\delta} = \frac{K(T_Z s+1)}{s(T_{P1}s+1)(T_{P2}s+1)}$$

Third order

Figure 2.2 . Nomoto Transfer Functions

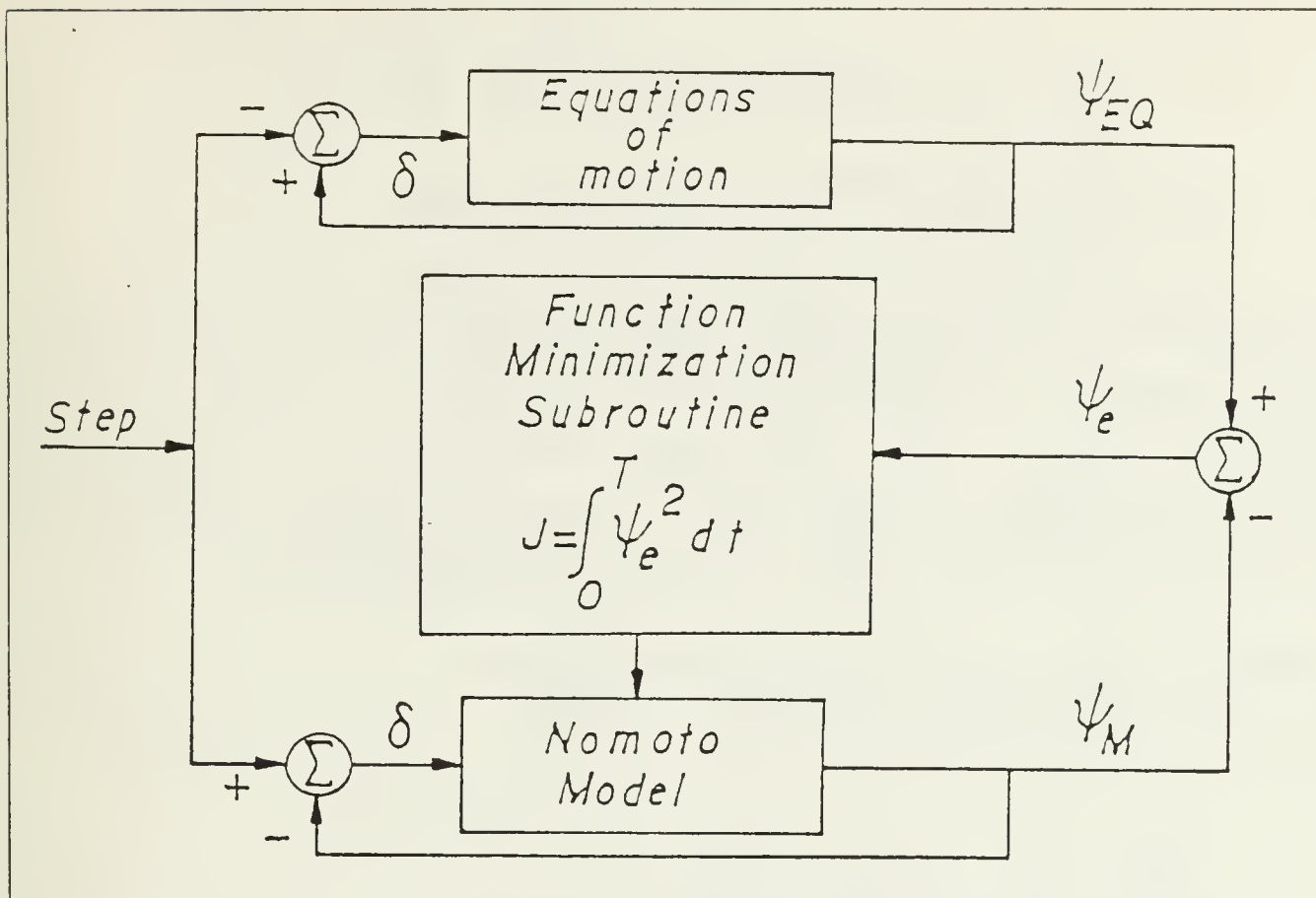


Figure 2.3 Nomoto Model Determination Scheme

representation was adopted because the system is dynamic and use of the Nomoto model representation implies additional computer use. On the other hand, frequency domain studies were carried out using the Nomoto representation since this representation is easier handled.

### III. AN ADEQUATE PERFORMANCE CRITERION

#### A. CRITERION BASED ON TRUE ADDED RESISTANCE

The performance criterion which characterizes propulsion losses due to steering may be shown to be that derived from excess power consumption per unit distance caused due to steering [Ref. 1, 6]. The added resistance due to steering can be related to the surge or thrust equation where the total instantaneous surge relevant to steering is

$$\Delta X = [m + (\rho/2) L A X'_{vr}] vr + 1/2 [(\rho/2) A X'_{vv}] v^2 + 1/2 [(\rho/2) A X'_{\delta\delta} U^2] \delta^2 \quad (3.1)$$

where  $m$  = mass of ship

$\rho$  = density of sea water

$L$  = ship's length between perpendiculars

$A = L^2$

$U$  = ship's water speed

$v$  = sway velocity

$r$  = yaw rate of ship

$\delta$  = rudder angle

$X'_{vr}$  = force coefficient due to yaw/sway (positive)

$X'_{\delta\delta}$  = force coefficient due to rudder angle (negative)

$X'_{vv}$  = force coefficient due to sway

Since the sway velocity of the ship is small we can neglect the term which includes the square of the sway velocity in the previous equation. From this the mean surge relevant to steering may be written as

$$\overline{\Delta X} = [m + (\rho/2)LA X'_{vr}] (u_a r_a / 2) \cos(\varphi_v - \varphi_r) + [(\rho/2)A X'_{\delta\delta} U^2] (\delta^2 / 2) \quad (3.2)$$

Where  $u_a$  = amplitude of sway velocity  
 $r_a$  = amplitude of yaw rate  
 $\delta_a$  = amplitude of rudder angle  
 $\varphi_v - \varphi_r$  = phase difference between sway and yaw rate

A performance criterion for added resistance due to steering may be formulated as

$$J = \lim_{T \rightarrow \infty} (1/2T) \int_0^T (-\sigma v r + \gamma U^2 \delta^2) dt \quad (3.3)$$

where  $\sigma$  and  $\gamma$  are constants

Accurate knowledge of the nonlinear coefficients  $X'_{vr}$  and  $X'_{\delta\delta}$  is required for the accuracy of such a criterion. In addition the criterion itself suffers from the disadvantage that sway velocity measurements are not available. Normalizing the last equation the performance criterion will be

$$J_{norm} = \lim_{T \rightarrow \infty} (1/2T) \int_0^T (-\lambda'' v r + \delta^2) dt \quad (3.4)$$

where  $\lambda'' = \{2[m + (\rho/2)LA]X'_{vr}\} / [(\rho/2)X'_{\delta\delta} U^2]$

Table I indicates the values of  $\lambda''$  for the operating range of speed of the ship studied.

TABLE I  
Weighting factor  $\lambda''$

| Ship's speed (knots) | $\lambda''$ |
|----------------------|-------------|
| 16                   | 21.5350     |
| 23                   | 10.4215     |
| 32                   | 5.3900      |

## B. CRITERION BASED ON APPROXIMATE ADDED RESISTANCE

Empirical criteria based on an approximation to added resistance may also be derived. A semiempirical criterion for measuring the relative performance was developed [Ref. 7], based on the assumption of small amplitude oscillations around the steady-state pivot point of the ship during yawing at the ship/steering system natural frequency. This may be extended and an alternative criterion for added resistance will be

$$J = \lim_{T \rightarrow \infty} (1/2T) \int_0^T (\lambda \psi_e^2 + \delta^2) dt \quad (3.5)$$

where

$$\lambda = \lambda' \omega = [2m(1 + X'_{vr})(\overline{OP}/L\omega^2)] / [(\rho/2)LX'_{\delta\delta}U^2]$$

$$X'_{vr} = [(\rho/2)LAX'_{vr}] / m$$

$\overline{OP}$  = distance from center of gravity to pivot center

$\omega$  = natural frequency (closed loop ship steering control)

$\psi_e$  = ship's perturbation yaw angle

The values of  $\lambda'$  as a function of ship's speed are given by Table II.

A closed loop system natural frequency  $\omega$  of around 0.05 rads per sec has the potential to attenuate the effects of

TABLE II  
Weighting factor  $\lambda'$

| Ship's speed (knots) | $\lambda'$ |
|----------------------|------------|
| 16                   | 6,720      |
| 23                   | 3,251      |
| 32                   | 1,680      |

seaway disturbance in the range of encounter angles where added resistance due to steering is important [Ref. 6]. The weighting factor for the operating range of the ship is shown in Table III.

TABLE III  
Weighting factor  $\lambda$

| Ship's speed (knots) | $\lambda$ |
|----------------------|-----------|
| 16                   | 16.796    |
| 23                   | 8.128     |
| 32                   | 4.2       |

Equation 3.5 is used as a performance criterion for this study. It is an approximation but it is convenient for onboard use since ship's perturbation yaw angle  $\psi$  and rudder angle  $\delta$  are measurable.

### C. WEIGHTING FACTOR STUDY

The weighting factor  $\lambda$  given by Table III used in equation 3.5, plays an important role in terms of the optimal controller parameters determination. Some investigation is necessary in order to verify the accuracy of the results, since the values of  $\lambda$  of Table III are determined based on the assumption that the closed loop system's natural frequency is around 0.05 rads per sec [Ref. 1]. Frequency domain techniques were used for this purpose. Using the Nomoto third order model representation of the ship and available controller parameters from Chapter 4 for sea state



4, encounter frequency 1.5 rads per sec, encounter angle  $150^\circ$  and ship's speed 23 knots we found that the closed loop bandwidth of the system is 0.04 rads per sec, as indicated in Figure 3.1, which is not close enough to 0.05 rads per sec.

For the same sea conditions and ship speed, with the assumption that the closed loop natural frequency of the system is not 0.05 rads per sec but 0.04 rads per sec, a new value  $\lambda=5.734$  was obtained and the frequency domain techniques result in a new bandwidth 0.035 rads per sec as is indicated in Figure 3.2.

Clearly, the values of  $\lambda$  given by Table III and used in this study are not the best. Unfortunately, since the full hydrodynamic coefficients of the SL-7 containership are not known we can't develop the surge equation and thus it is still impossible to determine accurate values for the weighting factor  $\lambda$ .

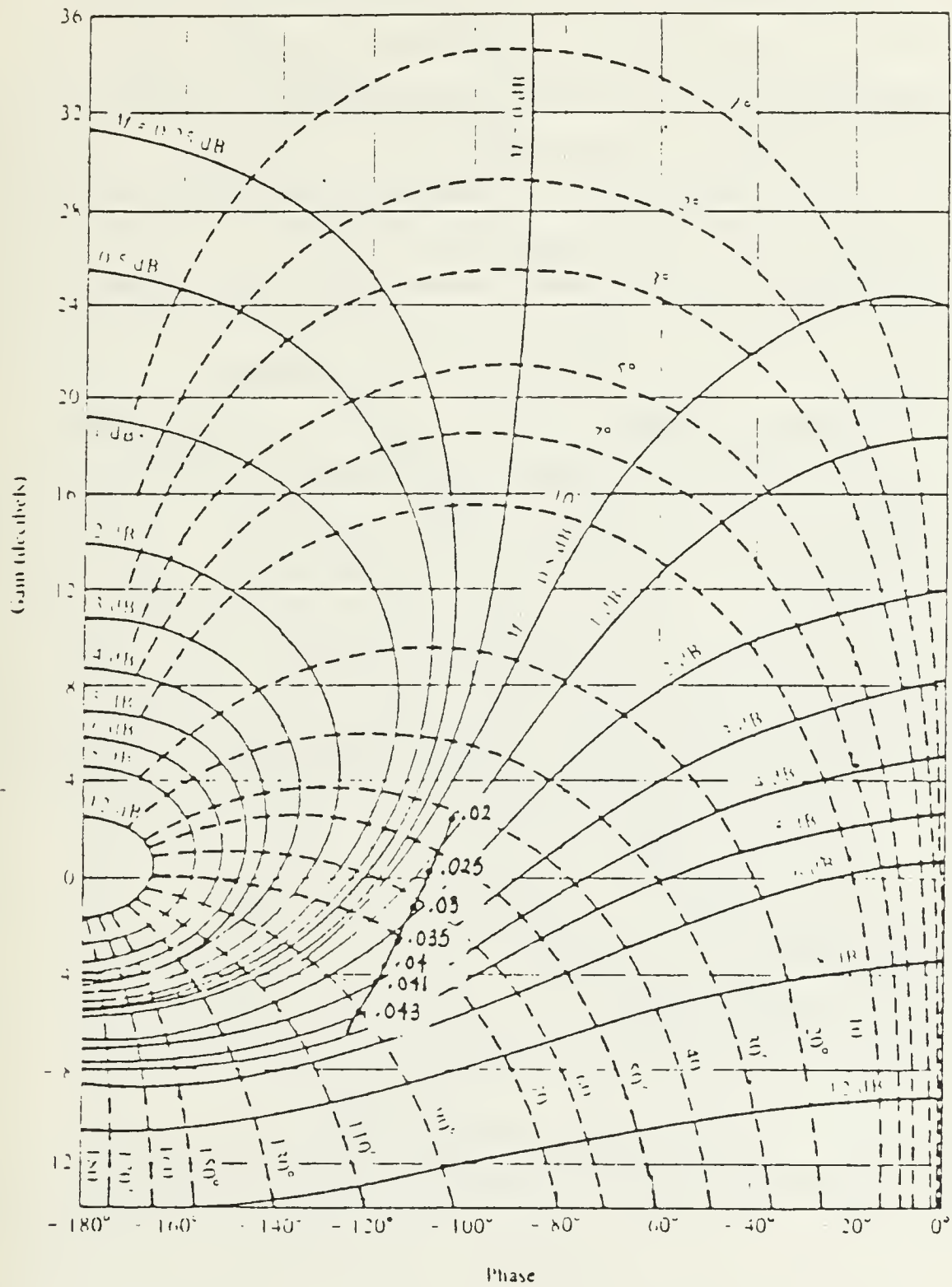


Figure 3.1 Closed Loop Bandwidth for  $\lambda=8.128$

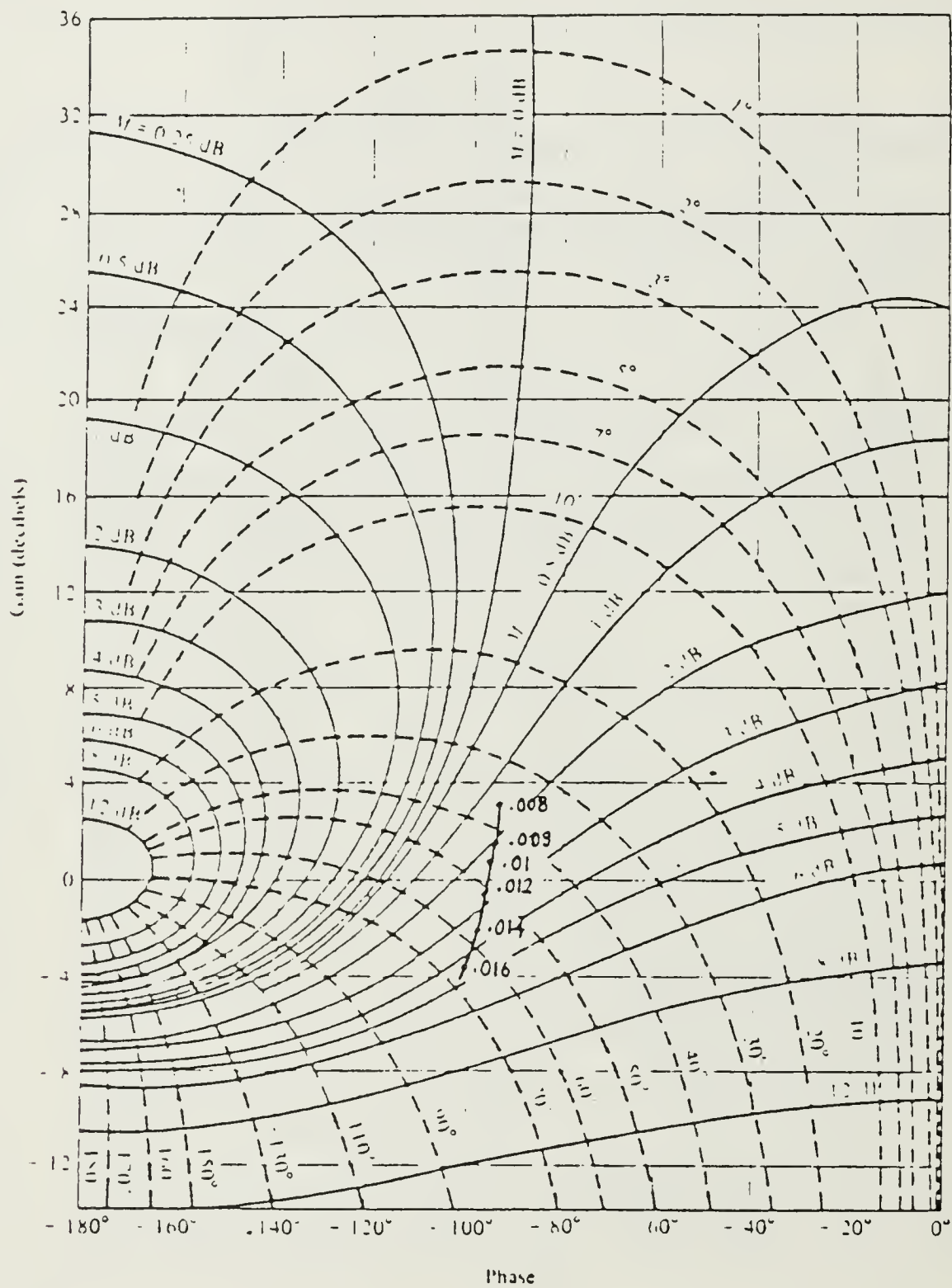


Figure 3.2 Closed Loop Bandwidth for  $\lambda=5.734$

#### IV. REGULAR SEAS - CONTROLLER DESIGN

We have already defined a suitable and sufficiently accurate ship computer model and the system's performance criterion, as well. The remaining task is to determine a representation of the external disturbances imparted to the ship by the sea, before the system's performance in a seaway can be evaluated. A correct model of the seaway itself is essential to representative modeling of forces and moments exerted on the ship by it.

At this point we will use the regular sea model as sea representation. The properties of regular seas are well defined. The wave crests are assumed to be straight, infinitely long, parallel and equally spaced with constant wave height. The waves progress in a direction perpendicular to the crest line at a uniform velocity. However the sea is never regular. It is a random phenomenon where waves are continually changing in height, length and breadth [Ref. 8].

The forces exerted by the regular sea have the form

$$F = \omega_d R_i \cos(\omega_e t + \psi_i) \quad (4.1)$$

where  $\omega_d$  = significant wave height  
 $R_i$  = exciting force  
 $\omega_e$  = encounter frequency  
 $\psi_i$  = phase angle

The correspondence between sea state and wave height is indicated in Table IV [Ref. 9].

The exciting forces  $R_i$  for different encounter frequencies and encounter angles were obtained from the sea state generator program [Ref. 10].

TABLE IV  
Sea state vs Wave height

| Sea state<br>(Beaufort scale) | Range for wave height<br>(Feet) |
|-------------------------------|---------------------------------|
| 0                             | 0.0                             |
| 1                             | 0.32                            |
| 2                             | 0.65-0.98                       |
| 3                             | 1.96-3.28                       |
| 4                             | 3.28-4.92                       |
| 5                             | 6.56-8.20                       |
| 6                             | 9.84-13.1                       |
| 7                             | 13.1-18.2                       |
| 8                             | 18.2-24.6                       |
| 9                             | 23.0-32.9                       |

Appendix B indicates the regular seastate formulation in the FORTRAN program used for obtaining the controller parameters.

The controller used in the entire study has one pole-one zero and the form is indicated in Figure 4.1. This controller seems to have the best performance in calm waters and in seaway [Ref. 5].

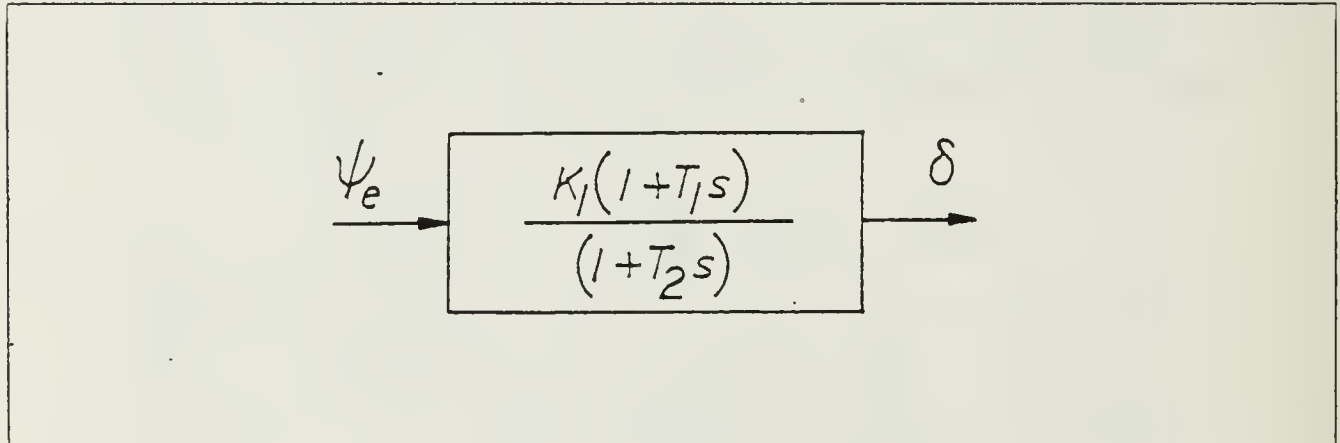


Figure 4.1 Controller Used in this Study

The optimized controller parameters and the cost  $J$  for 23 knots speed, sea states 4-6-7-9, different encounter angles and various encounter frequencies are indicated in Tables V, VI, VII and VIII.



Studying the Tables V through VIII we can draw the following conclusions:

- For a particular encounter angle and encounter frequency the higher the sea state the higher the cost.
- For the same sea state the cost becomes smaller for higher encounter frequencies.
- For encounter frequency 0.2 rads per sec the maximum cost occurs at  $60^\circ$  encounter angle for all tested sea states.
- For 0.6 and 0.75 rads per sec encounter frequency the maximum cost occurs at  $120^\circ$  encounter angle for all tested sea states.
- For 1.5 rads per sec encounter frequency the maximum cost occurs at  $90^\circ$  encounter angle for all tested sea states.
- For 0.4 rads per sec encounter frequency the maximum cost occurs at  $90^\circ$  encounter angle for sea states 4, 6 and 7 while at sea state 9 the maximum cost occurs at  $60^\circ$  encounter angle.

Appendix C provides the computer program necessary to achieve the system's response. Some typical responses are indicated in Figures 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9. It is obvious that as the sea state goes to heavier seas the rudder and yaw perturbations become larger.

An attempt to determine how accurate the controller parameters must be for a particular situation, leads to the conclusion that high accuracy isn't required. Keeping two parameters fixed each time and vary the third we can see (Figures 4.10, 4.11, 4.12, 4.13, 4.14) that the cost doesn't change appreciably in the vicinity of the actual value.

Figures 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9 indicate that the yaw and rudder excursions are less than  $1^\circ$ . This just seems strange, though it may be because of the optimization of the filter. We tried to investigate that by



using the optimal filter for sea state 9, encounter frequency 1.5 rads per sec, encounter angle  $120^\circ$  and run it in sea state 4, keeping the same encounter frequency and angle. The yaw and rudder excursions, even if they became larger, remained less than  $1^\circ$ . The parameters of those two filters are close and the reason might be the flatness of the cost surface. Second attempt led to more interesting results. Using the same filter and run it in sea state 4, encounter frequency 0.4 rads per sec and encounter angle  $060^\circ$ , the system becomes unstable (Figures 4.15, 4.16).

TABLE V  
Optimal Controller Parameters for Regular Sea  
Sea State 4

| Encounter Frequency 0.2 rads per sec |           |            |            |           |
|--------------------------------------|-----------|------------|------------|-----------|
| encounter<br>angle(degrees)          | K1        | T1         | T2         | J         |
| 0                                    | 0.5221067 | 66.3312231 | 12.8332741 | 0.609E-33 |
| 30                                   | 1.0488701 | 61.9309387 | 15.9266357 | 2.4819    |
| 60                                   | 1.2036362 | 54.5533295 | 16.0245972 | 3.612223  |
| 90                                   | 1.3178062 | 49.7426453 | 14.8329315 | 2.703524  |
| 120                                  | 1.3984699 | 46.9797058 | 13.9525757 | 1.355578  |
| 150                                  | 1.4502153 | 45.4263306 | 13.3351599 | 0.3567196 |
| 180                                  | 0.7195223 | 25.2119598 | 14.1219782 | 0.345E-28 |

| Encounter Frequency 0.4 rads per sec |           |            |            |           |
|--------------------------------------|-----------|------------|------------|-----------|
| encounter<br>angle(degrees)          | K1        | T1         | T2         | J         |
| 0                                    | 0.5221067 | 66.3312231 | 12.8332741 | 0.517E-35 |
| 30                                   | 0.7234516 | 74.7846533 | 47.9879893 | 0.54673   |
| 60                                   | 0.8730211 | 92.8420868 | 50.0454407 | 1.194746  |
| 90                                   | 2.8910360 | 28.9679871 | 10.0176315 | 2.536161  |
| 120                                  | 2.6232796 | 27.9702454 | 8.8327761  | 0.2349457 |
| 150                                  | 2.6408129 | 27.7937927 | 8.6838455  | 0.0545772 |
| 180                                  | 0.7195223 | 25.2119598 | 14.1219782 | 0.536E-32 |

| Encounter Frequency 0.6 rads per sec |           |            |            |           |
|--------------------------------------|-----------|------------|------------|-----------|
| encounter<br>angle(degrees)          | K1        | T1         | T2         | J         |
| 0                                    | 0.5221067 | 66.3312231 | 12.8332741 | 0.453E-31 |
| 30                                   | 2.0506487 | 1.2107763  | 5.5998001  | 0.0028366 |
| 60                                   | 1.0504951 | 0.2329917  | 19.0010876 | 0.0031525 |
| 90                                   | 2.1496201 | 1.2607498  | 5.3318434  | 0.0790777 |
| 120                                  | 2.1221027 | 0.9715905  | 6.9064713  | 0.0796856 |
| 150                                  | 1.9617786 | 0.8480816  | 8.3953667  | 0.0341976 |
| 180                                  | 0.7195223 | 25.2119598 | 14.1219782 | 0.147E-39 |

| Encounter Frequency 0.75 rads per sec |           |            |            |           |
|---------------------------------------|-----------|------------|------------|-----------|
| encounter<br>angle(degrees)           | K1        | T1         | T2         | J         |
| 0                                     | 0.5221067 | 66.3312231 | 12.8332741 | 0.711E-35 |
| 30                                    | 2.4342451 | 0.8039263  | 7.4397717  | 0.0017128 |
| 60                                    | 2.3829517 | 0.8094406  | 8.6272535  | 0.0042339 |
| 90                                    | 2.0794163 | 0.4690621  | 16.9594727 | 0.0442135 |
| 120                                   | 1.9938784 | 0.2545378  | 22.4892426 | 0.1164415 |
| 150                                   | 1.9387684 | 0.2628353  | 23.8461609 | 0.0379958 |
| 180                                   | 0.7195223 | 25.2119598 | 14.1219782 | 0.312E-23 |

| Encounter Frequency 1.5 rads per sec |           |            |            |           |
|--------------------------------------|-----------|------------|------------|-----------|
| encounter<br>angle(degrees)          | K1        | T1         | T2         | J         |
| 0                                    | 0.5221067 | 66.3312231 | 12.8332741 | 0.143E-35 |
| 30                                   | 1.8784037 | 0.6553955  | 5.4344263  | 0.0000847 |
| 60                                   | 2.4894753 | 0.5992758  | 5.1160698  | 0.0014724 |
| 90                                   | 2.5899792 | 0.6663168  | 3.1813316  | 0.0241299 |
| 120                                  | 1.8784037 | 0.5395500  | 10.4344263 | 0.0028635 |
| 150                                  | 2.4478331 | 0.5559916  | 5.9208412  | 0.0015984 |
| 180                                  | 0.7195223 | 25.2119598 | 14.1219782 | 0.451E-28 |

TABLE VI  
Optimal Controller Parameters for Regular Sea  
Sea State 6

| Encounter Frequency 0.2 rads per sec  |           |            |            |           |
|---------------------------------------|-----------|------------|------------|-----------|
| encounter<br>angle(degrees)           | K1        | T1         | T2         | J         |
| 0                                     | 0.5221067 | 66.3312231 | 12.8332741 | 0.322E-33 |
| 30                                    | 1.0966187 | 62.3766327 | 19.3941193 | 8.622314  |
| 60                                    | 1.2665367 | 55.1072540 | 19.2263336 | 11.84099  |
| 90                                    | 1.3603411 | 49.3086395 | 16.7315979 | 9.270265  |
| 120                                   | 1.4170542 | 46.4313202 | 14.7203903 | 5.004774  |
| 150                                   | 1.4533644 | 45.2830963 | 13.6198730 | 1.396385  |
| 180                                   | 0.7195223 | 25.2119598 | 14.1219782 | 0.678E-28 |
| Encounter Frequency 0.4 rads per sec  |           |            |            |           |
| encounter<br>angle(degrees)           | K1        | T1         | T2         | J         |
| 0                                     | 0.5221067 | 66.3312231 | 12.8332741 | 0.122E-31 |
| 30                                    | 0.7536127 | 12.4472111 | 4.8151121  | 2.3798    |
| 60                                    | 1.1621914 | 1.7206783  | 5.6173820  | 4.143427  |
| 90                                    | 2.8681517 | 28.5688019 | 11.3736725 | 7.7779746 |
| 120                                   | 2.6123600 | 28.0108032 | 9.1387405  | 0.8634676 |
| 150                                   | 2.6361399 | 27.8540497 | 8.7665482  | 0.2140626 |
| 180                                   | 0.7195223 | 25.2119598 | 14.1219782 | 0.345E-25 |
| Encounter Frequency 0.6 rads per sec  |           |            |            |           |
| encounter<br>angle(degrees)           | K1        | T1         | T2         | J         |
| 0                                     | 0.5221067 | 66.3312231 | 12.8332741 | 0.806E-35 |
| 30                                    | 2.0449467 | 1.2405663  | 5.5909785  | 0.0113364 |
| 60                                    | 1.0594482 | 0.1432046  | 18.5202637 | 0.0126108 |
| 90                                    | 2.1537333 | 1.1794500  | 5.9987049  | 0.2766824 |
| 120                                   | 2.1456242 | 0.9514294  | 7.3327799  | 0.3125796 |
| 150                                   | 1.9752455 | 0.8255181  | 8.5351868  | 0.1364259 |
| 180                                   | 0.7195223 | 25.2119598 | 14.1219782 | 0.112E-23 |
| Encounter Frequency 0.75 rads per sec |           |            |            |           |
| encounter<br>angle(degrees)           | K1        | T1         | T2         | J         |
| 0                                     | 0.5221067 | 66.3312231 | 12.8332741 | 0.753E-32 |
| 30                                    | 2.4413719 | 0.7599964  | 7.3472633  | 0.0068484 |
| 60                                    | 2.4142313 | 0.7818718  | 8.5500679  | 0.0169234 |
| 90                                    | 2.0592680 | 0.3840635  | 19.2782745 | 0.1523162 |
| 120                                   | 2.0695038 | 0.2843146  | 22.5692444 | 0.4640285 |
| 150                                   | 1.9513931 | 1.2351496  | 23.5140228 | 0.1518951 |
| 180                                   | 0.7195223 | 25.2119598 | 14.1219782 | 0.691E-28 |
| Encounter Frequency 1.5 rads per sec  |           |            |            |           |
| encounter<br>angle(degrees)           | K1        | T1         | T2         | J         |
| 0                                     | 0.5221067 | 66.3312231 | 12.8332741 | 0.321E-33 |
| 30                                    | 1.7606564 | 0.4668925  | 12.3475494 | 0.0003390 |
| 60                                    | 2.5002985 | 0.5747030  | 5.3262844  | 0.0058868 |
| 90                                    | 2.6015043 | 0.6543975  | 3.2408133  | 0.0946725 |
| 120                                   | 2.1809998 | 0.4698086  | 10.9160814 | 0.0114672 |
| 150                                   | 2.4302263 | 0.5666089  | 6.0247307  | 0.0063947 |
| 180                                   | 0.7195223 | 25.2119598 | 14.1219782 | 0.344E-23 |

TABLE VII  
Optimal Controller Parameters for Regular Sea  
Sea State 7

| Encounter Frequency 0.2 rads per sec |           |            |            |           |
|--------------------------------------|-----------|------------|------------|-----------|
| encounter<br>angle(degrees)          | K1        | T1         | T2         | J         |
| 0                                    | 0.5221067 | 66.3312231 | 12.8332741 | 0.911E-35 |
| 30                                   | 1.1839037 | 68.3722687 | 27.3912964 | 19.62723  |
| 60                                   | 1.3688898 | 65.5752258 | 30.9693604 | 24.53816  |
| 90                                   | 1.4492817 | 53.9667511 | 23.6652069 | 20.31325  |
| 120                                  | 1.4652090 | 46.2668457 | 17.1322327 | 12.58828  |
| 150                                  | 1.4653692 | 44.8378906 | 14.1106033 | 4.036665  |
| 180                                  | 0.7195223 | 25.2119598 | 14.1219782 | 0.912E-32 |

| Encounter Frequency 0.4 rads per sec |           |            |            |           |
|--------------------------------------|-----------|------------|------------|-----------|
| encounter<br>angle(degrees)          | K1        | T1         | T2         | J         |
| 0                                    | 0.5221067 | 66.3312231 | 12.8332741 | 0.341E-30 |
| 30                                   | 0.6452138 | 38.7243542 | 11.6571761 | 0.0524352 |
| 60                                   | 2.2381306 | 1.0741718  | 9.7088852  | 10.22498  |
| 90                                   | 2.7780743 | 30.6558838 | 16.9282227 | 11.95129  |
| 120                                  | 2.5894566 | 28.1353302 | 10.0156784 | 2.098495  |
| 150                                  | 2.6306906 | 27.8760681 | 8.9550962  | 0.6211755 |
| 180                                  | 0.7195223 | 25.2119598 | 14.1219782 | 0.176E-35 |

| Encounter Frequency 0.6 rads per sec |           |            |            |           |
|--------------------------------------|-----------|------------|------------|-----------|
| encounter<br>angle(degrees)          | K1        | T1         | T2         | J         |
| 0                                    | 0.5221067 | 66.3312231 | 12.8332741 | 0.157E-31 |
| 30                                   | 2.0501146 | 1.2125063  | 5.5930214  | 0.0346353 |
| 60                                   | 1.0624285 | 0.1251755  | 18.0873718 | 0.0386276 |
| 90                                   | 2.1488247 | 0.9770966  | 8.1855469  | 0.6328694 |
| 120                                  | 2.1970577 | 0.8763103  | 8.4206886  | 0.9178923 |
| 150                                  | 2.0124264 | 0.8064904  | 8.9983368  | 0.4150548 |
| 180                                  | 0.7195223 | 25.2119598 | 14.1219782 | 0.441E-28 |

| Encounter Frequency 0.75 rads per sec |           |            |            |           |
|---------------------------------------|-----------|------------|------------|-----------|
| encounter<br>angle(degrees)           | K1        | T1         | T2         | J         |
| 0                                     | 0.5221067 | 66.3312231 | 12.8332741 | 0.238E-28 |
| 30                                    | 2.4456072 | 0.8701959  | 7.6628313  | 0.0209509 |
| 60                                    | 2.4188919 | 0.8008499  | 8.6116581  | 0.0517269 |
| 90                                    | 1.9072247 | 0.1301596  | 28.8665771 | 0.4958954 |
| 120                                   | 2.2209492 | 0.3453745  | 22.8497772 | 1.398130  |
| 150                                   | 2.0318069 | 0.2577103  | 23.6702576 | 0.4641950 |
| 180                                   | 0.7195223 | 25.2119598 | 14.1219782 | 0.542E-21 |

| Encounter Frequency 1.5 rads per sec |           |            |            |           |
|--------------------------------------|-----------|------------|------------|-----------|
| encounter<br>angle(degrees)          | K1        | T1         | T2         | J         |
| 0                                    | 0.5221067 | 66.3312231 | 12.8332741 | 0.712E-32 |
| 30                                   | 2.0834208 | 0.4371362  | 15.1762695 | 0.0010384 |
| 60                                   | 2.4635468 | 0.5746776  | 5.3325920  | 0.0180051 |
| 90                                   | 2.6105270 | 0.6474890  | 3.4996614  | 0.2765892 |
| 120                                  | 2.1780138 | 0.4588630  | 11.4343033 | 0.0352355 |
| 150                                  | 2.4314880 | 0.5580992  | 6.0874767  | 0.0195939 |
| 180                                  | 0.7195223 | 25.2119598 | 14.1219782 | 0.413E-26 |



TABLE VIII

Optimal Controller Parameters for Regular Sea  
Sea State 9

| Encounter Frequency 0.2 rads per sec  |           |            |            |           |
|---------------------------------------|-----------|------------|------------|-----------|
| encounter<br>angle(degrees)           | K1        | T1         | T2         | J         |
| 0                                     | 0.5221067 | 66.3312231 | 12.8332741 | 0.493E-31 |
| 30                                    | 1.2344990 | 97.2906342 | 53.3980713 | 31.88802  |
| 60                                    | 1.5019569 | 77.3820190 | 45.6973572 | 30.87321  |
| 90                                    | 1.5020103 | 77.2400513 | 45.6112671 | 30.87321  |
| 120                                   | 1.5420017 | 51.2350922 | 23.8943634 | 21.75188  |
| 150                                   | 1.4879055 | 44.4281464 | 15.2255249 | 8.599576  |
| 180                                   | 0.7195223 | 25.2119598 | 14.1219782 | 0.810E-39 |
| Encounter Frequency 0.4 rads per sec  |           |            |            |           |
| encounter<br>angle(degrees)           | K1        | T1         | T2         | J         |
| 0                                     | 0.5221067 | 66.3312231 | 12.8332741 | 0.743E-33 |
| 30                                    | 0.1618259 | 95.8238471 | 18.3397064 | 8.103665  |
| 60                                    | 2.3103380 | 0.9894915  | 12.5459442 | 20.30595  |
| 90                                    | 3.3482129 | 2.6129665  | 4.7000313  | 7.494904  |
| 120                                   | 2.5573978 | 28.7854462 | 12.1667938 | 3.113852  |
| 150                                   | 2.6185656 | 27.9137726 | 9.3553696  | 1.324692  |
| 180                                   | 0.7195223 | 25.2119598 | 14.1219782 | 0.534E-33 |
| Encounter Frequency 0.6 rads per sec  |           |            |            |           |
| encounter<br>angle(degrees)           | K1        | T1         | T2         | J         |
| 0                                     | 0.5221067 | 66.3312231 | 12.8332741 | 0.478E-31 |
| 30                                    | 2.0493793 | 1.2093735  | 5.6404839  | 0.0820505 |
| 60                                    | 1.1003008 | 0.1920759  | 18.7369995 | 0.0919840 |
| 90                                    | 2.0454016 | 0.5407953  | 15.4096680 | 1.031631  |
| 120                                   | 2.2776527 | 0.7766371  | 10.4350891 | 2.069717  |
| 150                                   | 2.0829115 | 0.7725539  | 9.8721237  | 0.9771649 |
| 180                                   | 0.7195223 | 25.2119598 | 14.1219782 | 0.117E-29 |
| Encounter Frequency 0.75 rads per sec |           |            |            |           |
| encounter<br>angle(degrees)           | K1        | T1         | T2         | J         |
| 0                                     | 0.5221067 | 66.3312231 | 12.8332741 | 0.872E-35 |
| 30                                    | 2.4433956 | 0.8601446  | 7.7009745  | 0.0497640 |
| 60                                    | 2.4255047 | 0.7809458  | 8.7044067  | 0.1226490 |
| 90                                    | 2.2933350 | 0.4751374  | 16.7149658 | 0.7522082 |
| 120                                   | 2.3928595 | 0.4103206  | 22.9515076 | 3.146294  |
| 150                                   | 2.1456175 | 0.2891768  | 23.5924225 | 1.097565  |
| 180                                   | 0.7195223 | 25.2119598 | 14.1219782 | 0.611E-26 |
| Encounter Frequency 1.5 rads per sec  |           |            |            |           |
| encounter<br>angle(degrees)           | K1        | T1         | T2         | J         |
| 0                                     | 0.5221067 | 66.3312231 | 12.8332741 | 0.242E-33 |
| 30                                    | 2.0808840 | 0.4744592  | 16.3423157 | 0.0024732 |
| 60                                    | 2.4694090 | 0.5775681  | 5.4030972  | 0.0042757 |
| 90                                    | 2.6412249 | 0.6233797  | 3.9802380  | 0.6127556 |
| 120                                   | 2.1955976 | 0.4414446  | 12.1491365 | 0.0084519 |
| 150                                   | 2.4388838 | 0.5490999  | 6.1774960  | 0.0046688 |
| 180                                   | 0.7195223 | 25.2119598 | 14.1219782 | 0.420E-30 |

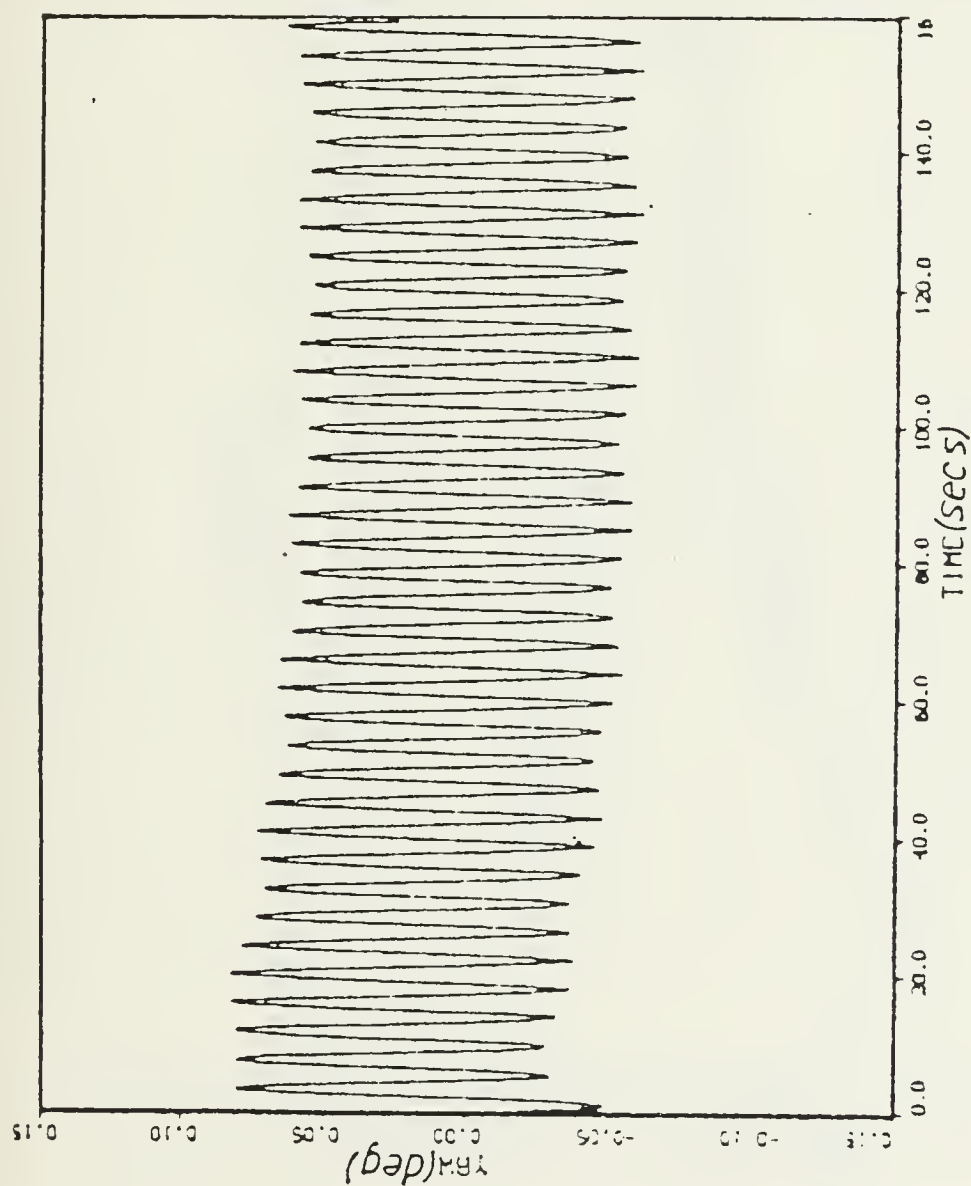


Figure 4.2 Yaw vs Time, Sea State 4.  
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°



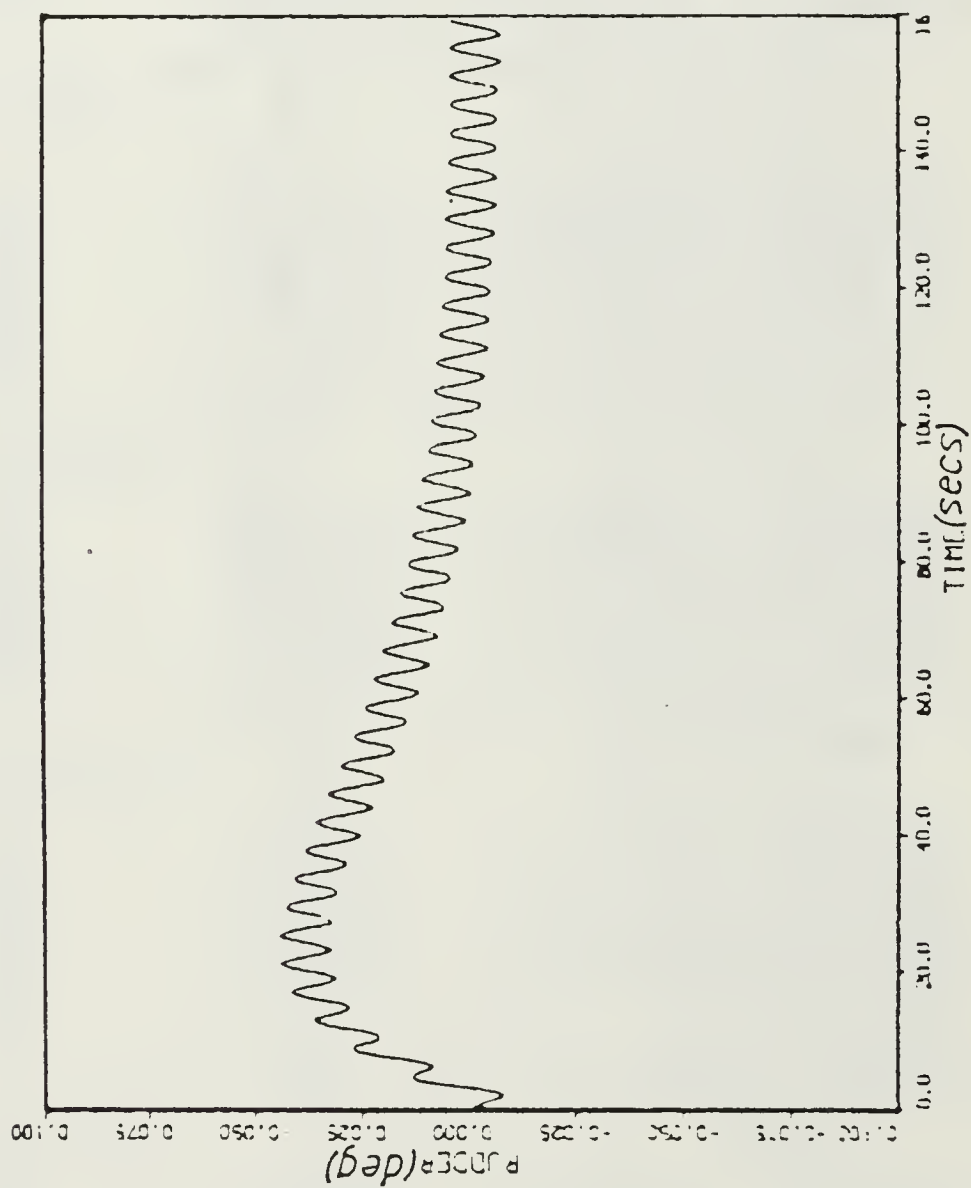


Figure 4.3 Rudder vs Time, Sea State 4.  
Encounter Frequency 1.5 rads per sec, Encounter Angle  $120^\circ$

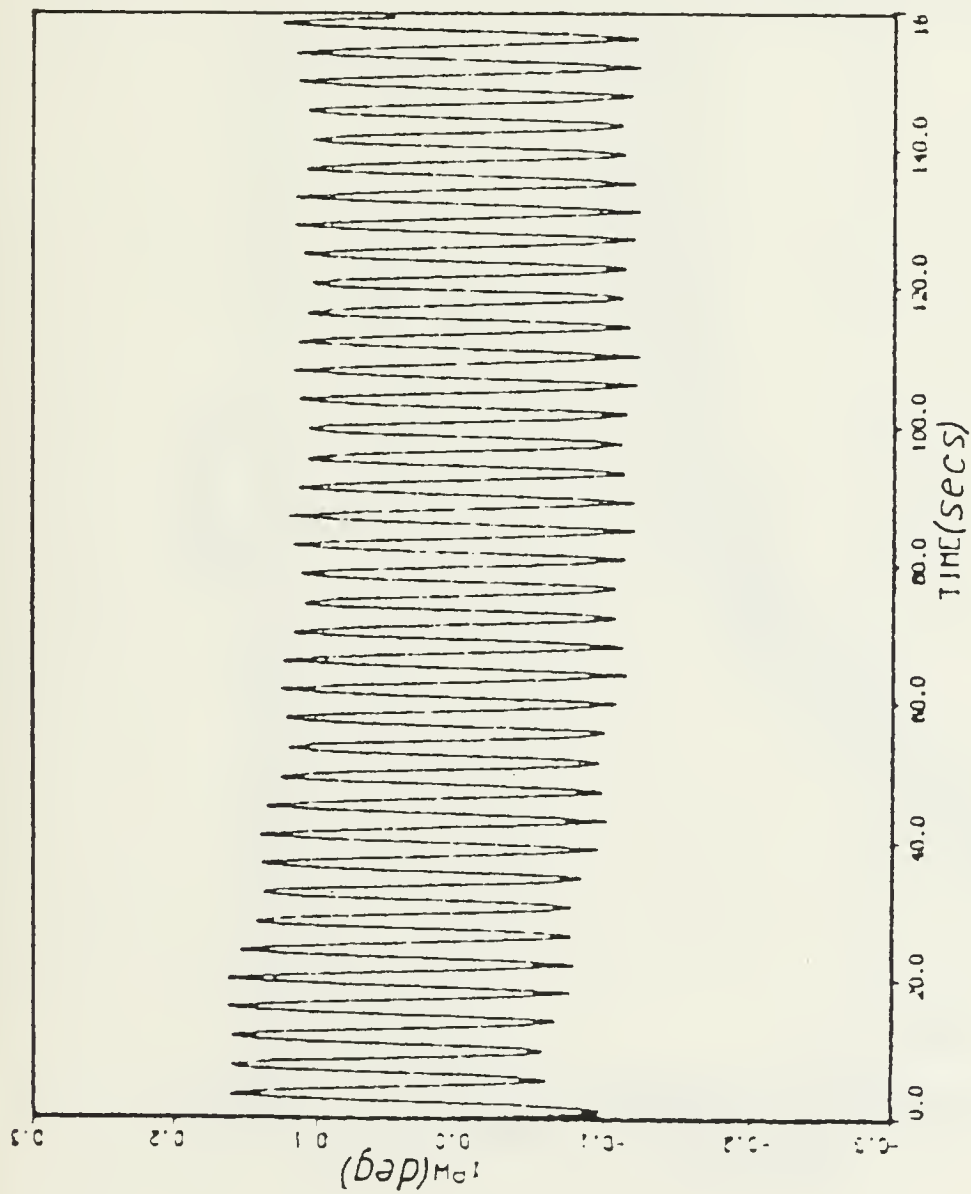


Figure 4.4 Yaw vs Time, Sea State 6.  
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°



Figure 4.5 Rudder vs Time, Sea State 6.  
Encounter Frequency 1.5 rads per sec, Encounter Angle  $120^\circ$

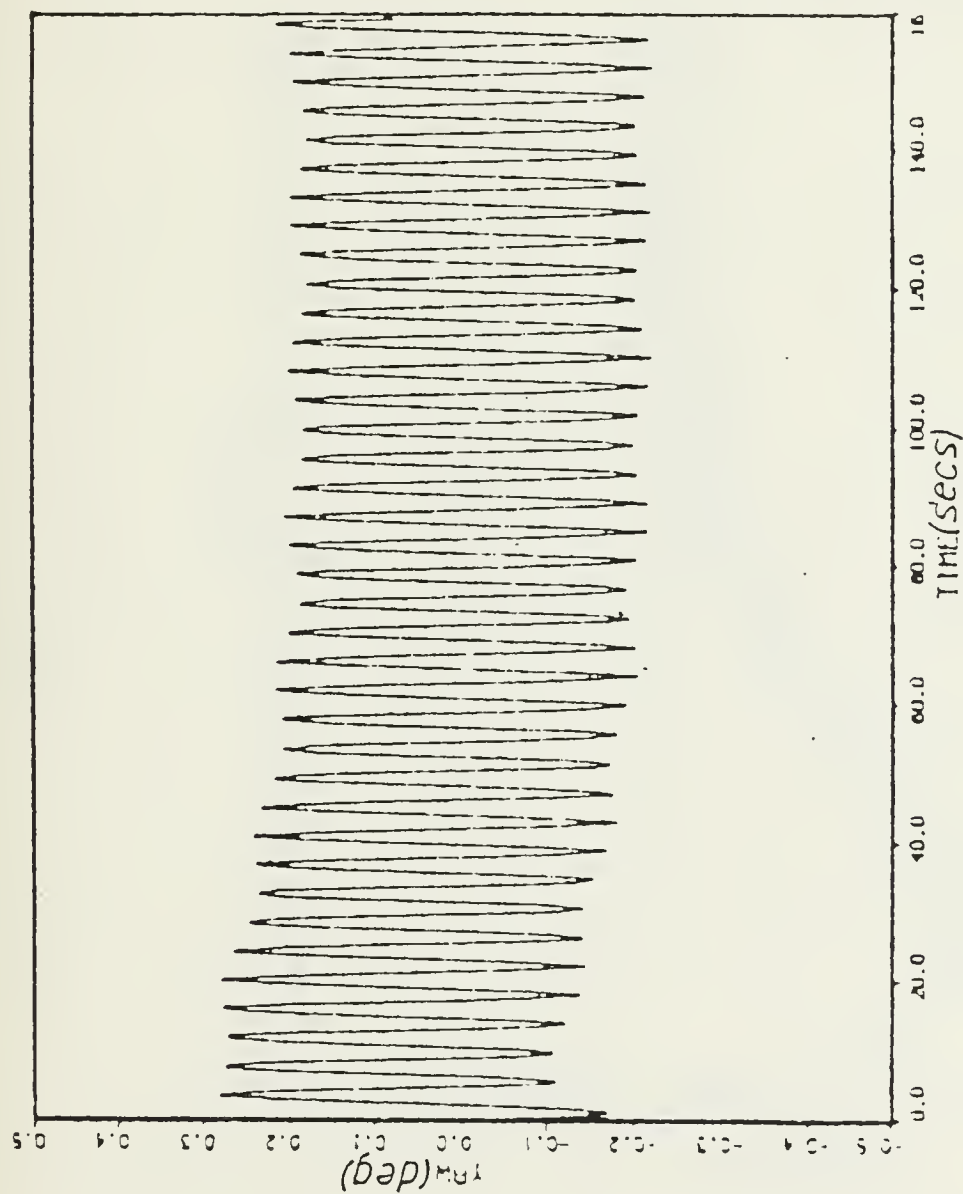


Figure 4.6 Yaw vs Time, Sea State 7.  
Encounter Frequency 1.5 rads per sec, Encounter Angle  $120^\circ$

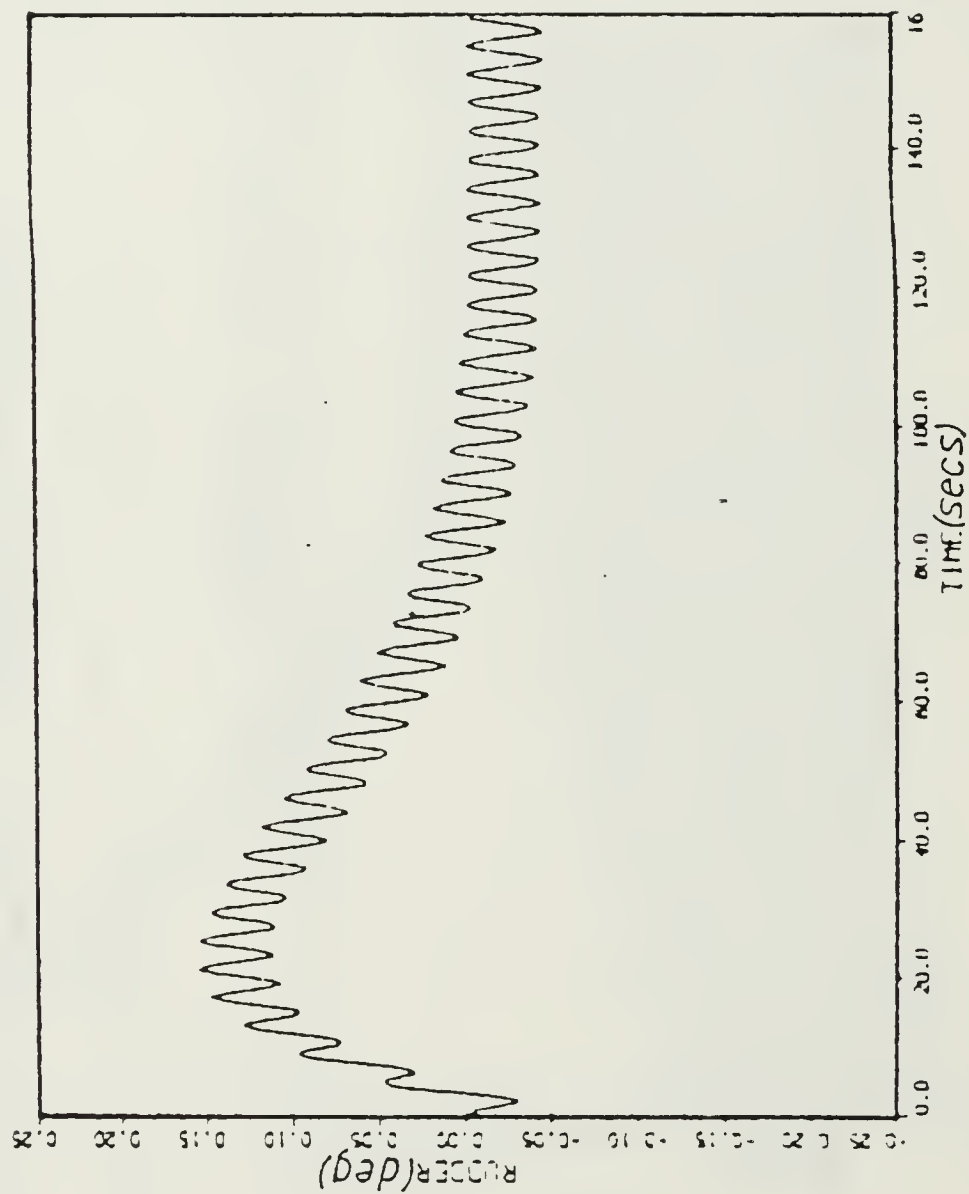


Figure 4.7 Rudder vs Time, Sea State 7.  
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°

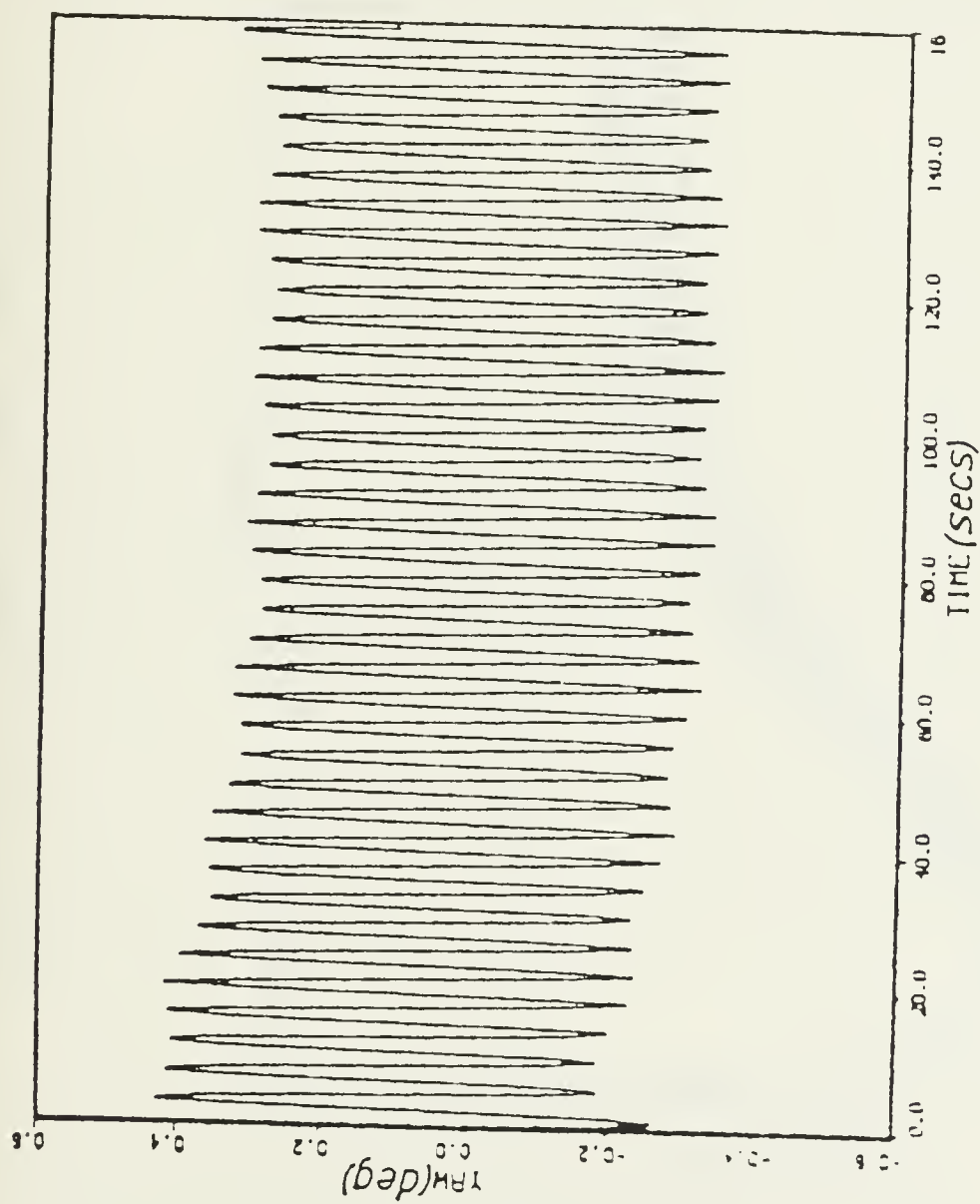


Figure 4.8 Yaw vs Time, Sea State 9.  
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°



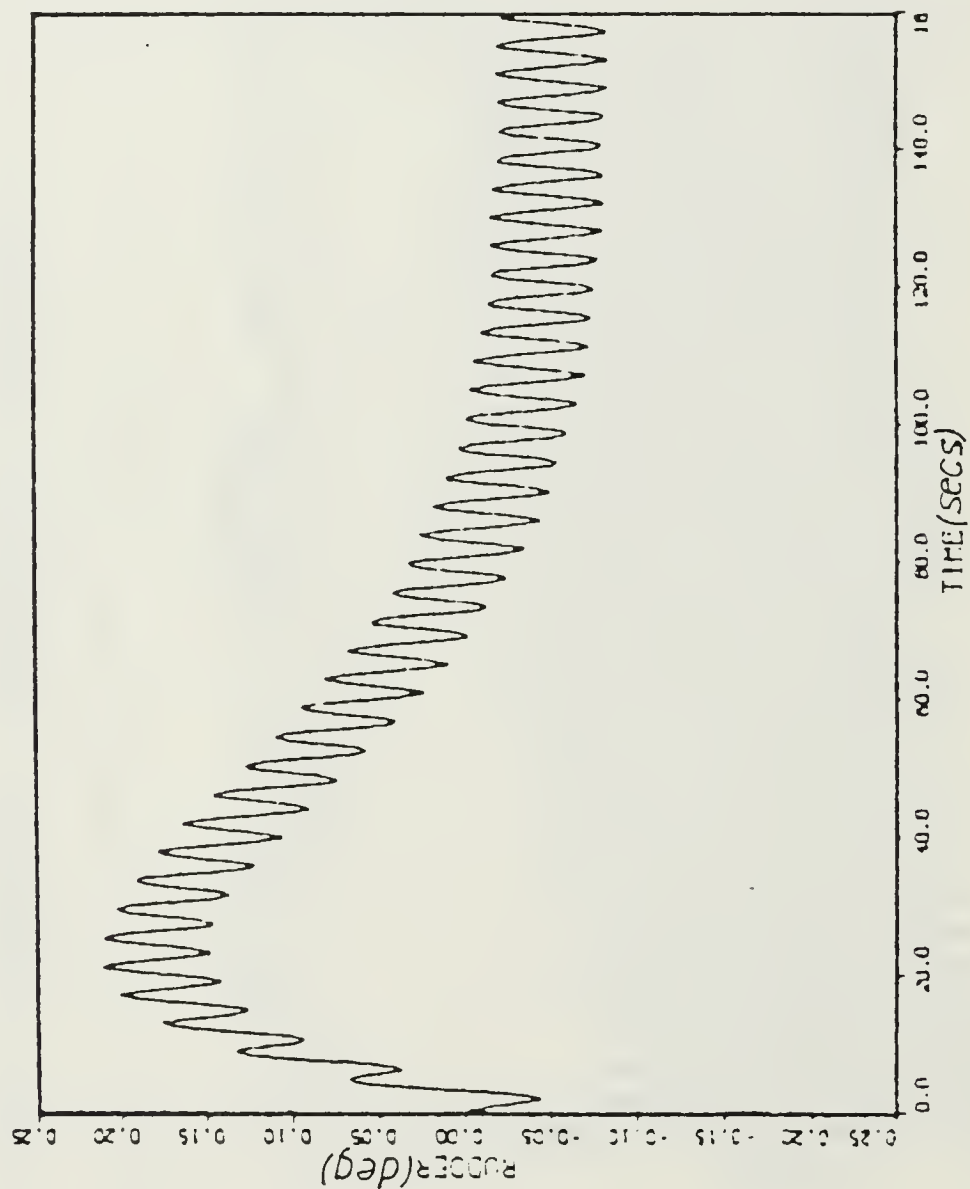


Figure 4.9 Rudder vs Time, Sea State 9.  
Encounter Frequency 1.5 rads per sec, Encounter Angle  $120^\circ$

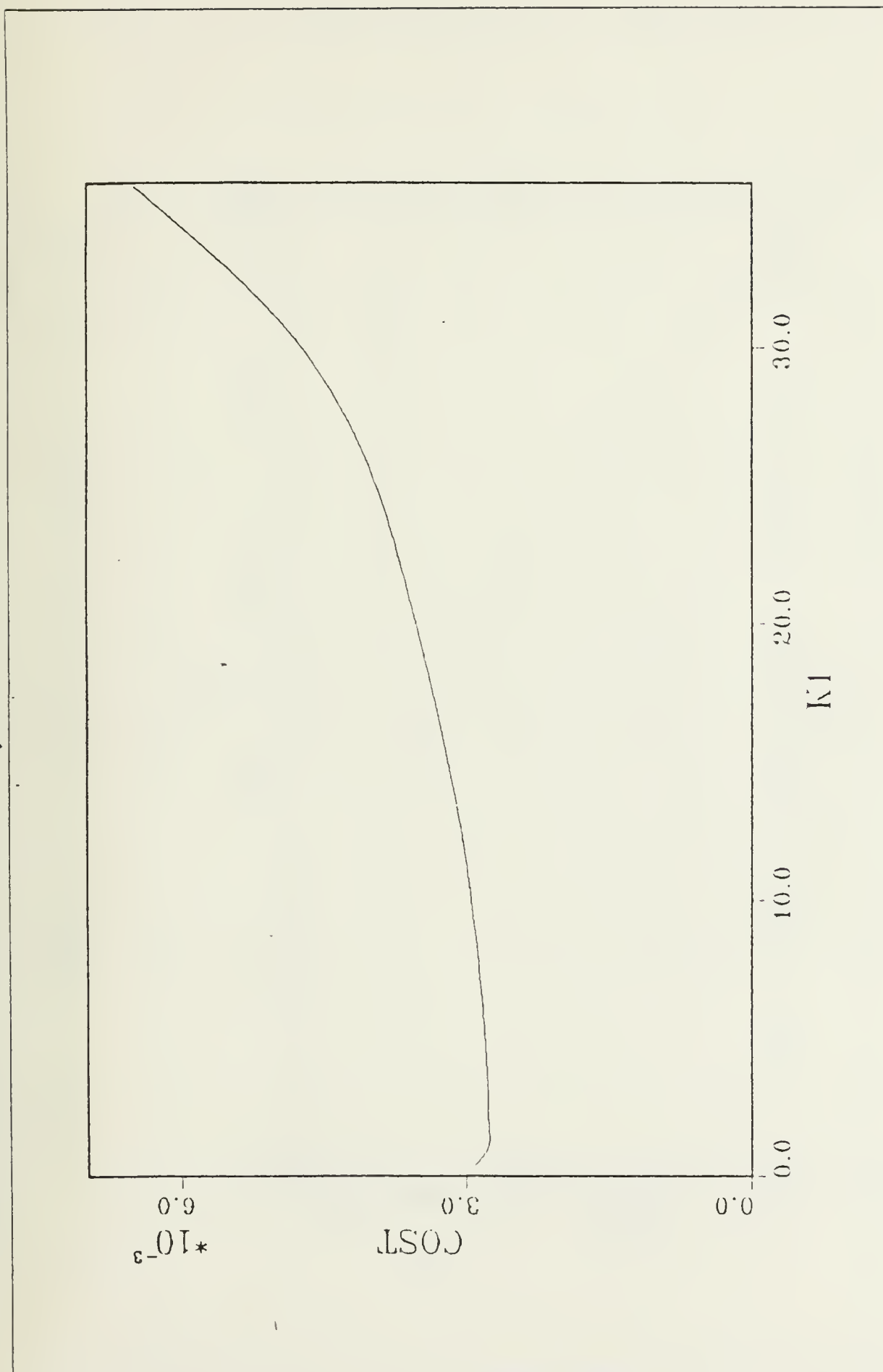


Figure 4.10 Cost vs Kl, Sea State 4.  
Encounter frequency 1.5 rads per sec, Encounter Angle  $120^\circ$

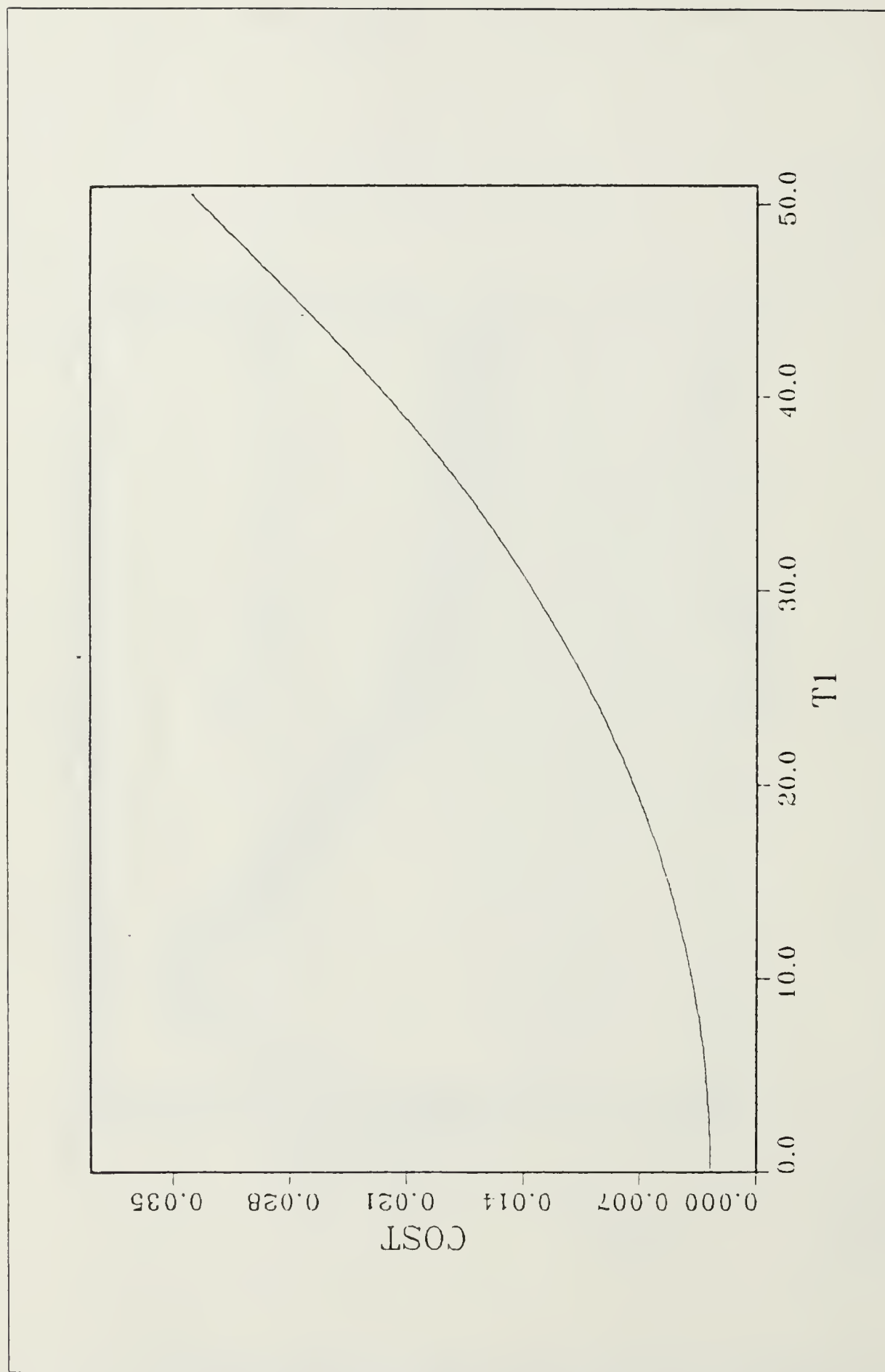


Figure 4.11 Cost vs T1, Sea State 4.  
Encounter frequency 1.5 rads per sec, Encounter Angle 120°

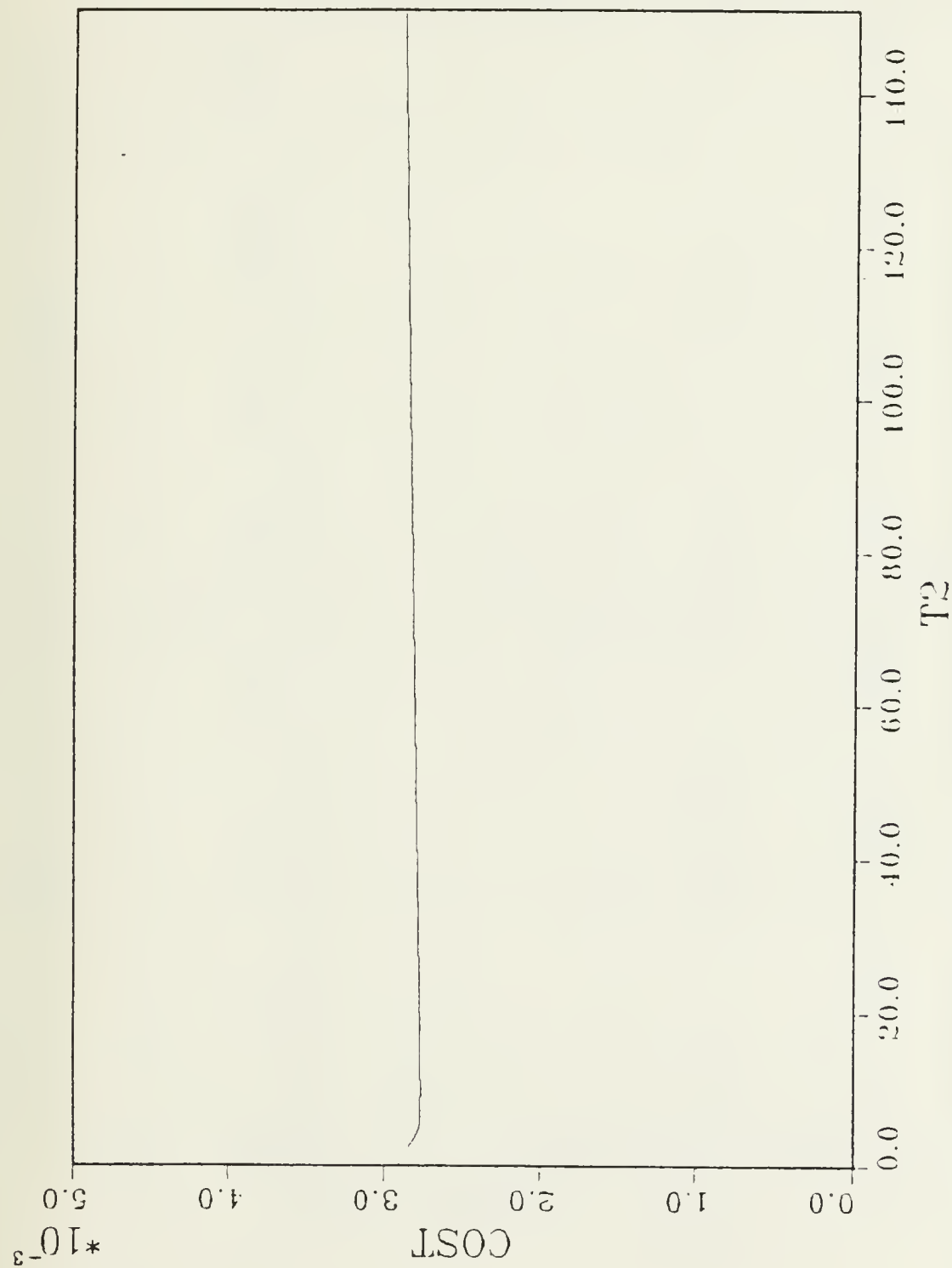


Figure 4.12 Cost vs T2, Sea State 4.  
Encounter frequency 1.5 rads per sec, Encounter Angle  $120^\circ$

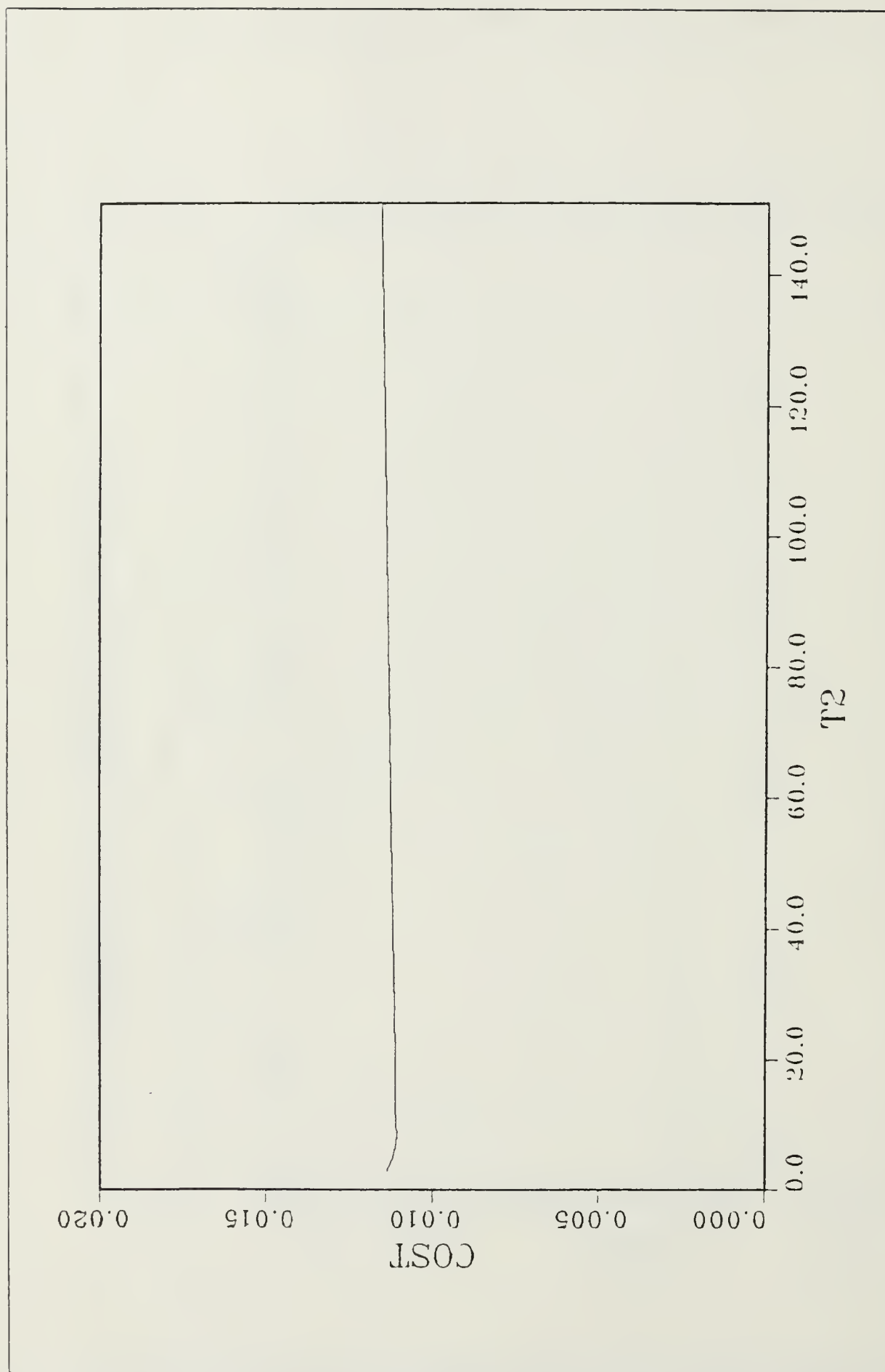


Figure 4.13 Cost vs T2, Sea State 6.  
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°



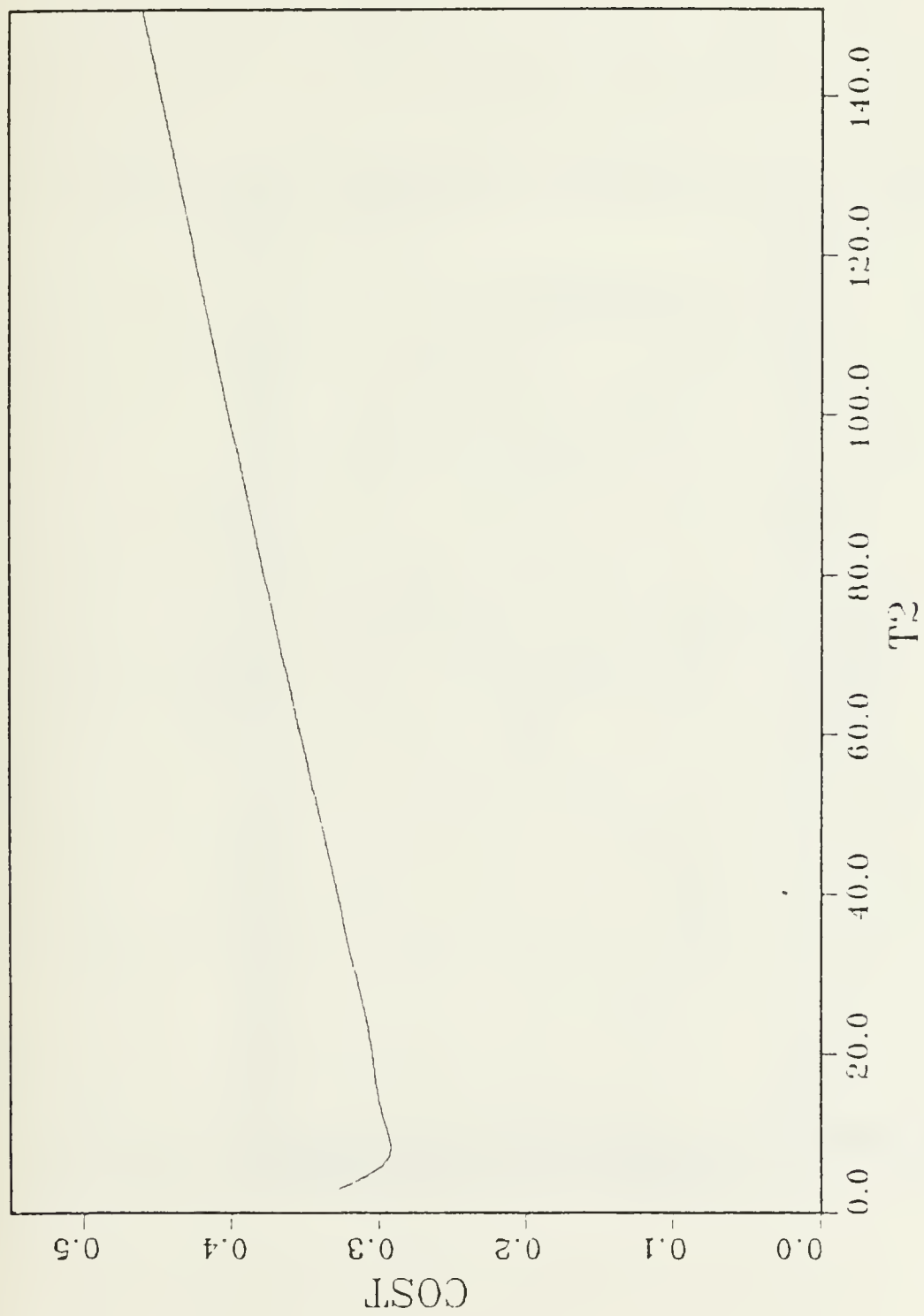


Figure 4.14 Cost vs T2, Sea State 6.  
Encounter Frequency 0.6 rads per sec, Encounter Angle  $90^\circ$

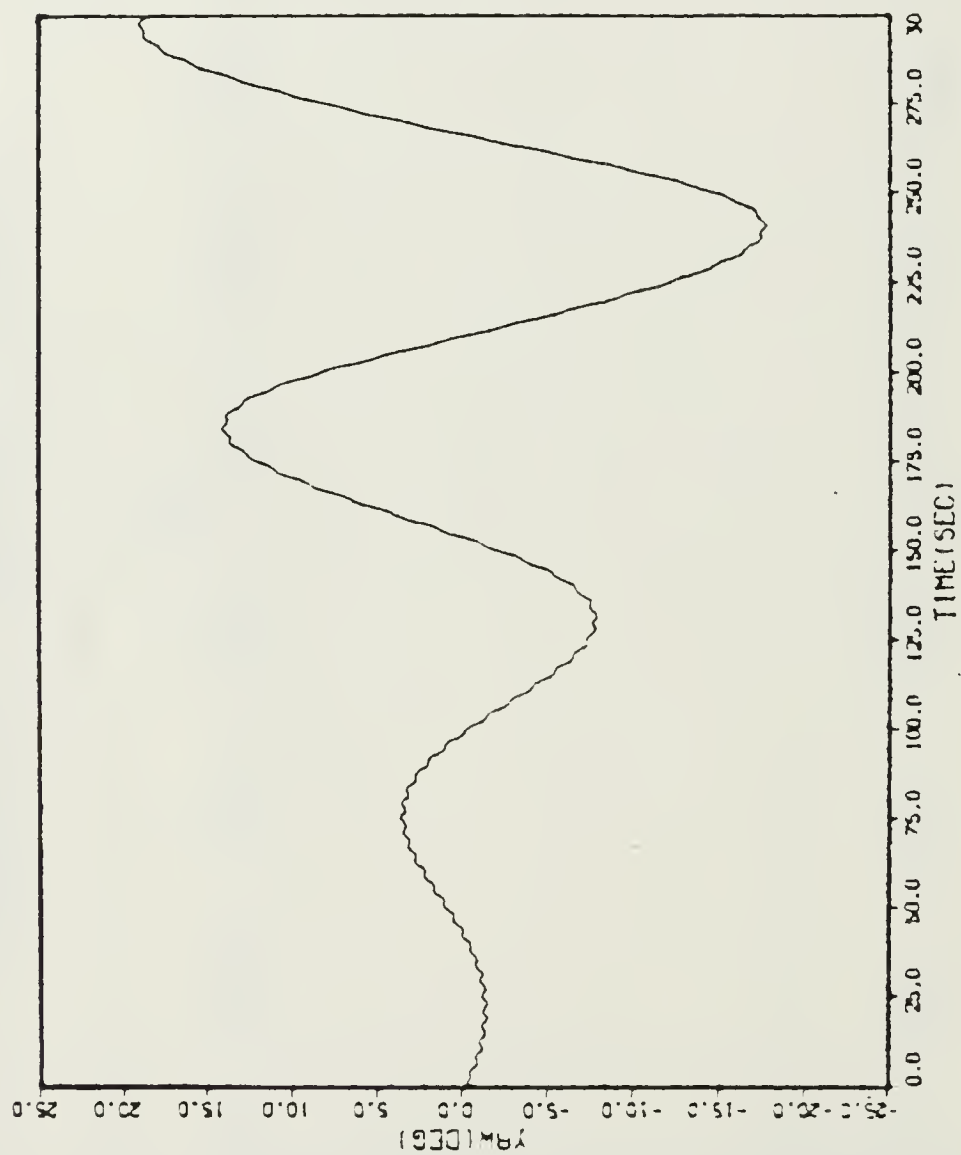


Figure 4.15 Yaw vs Time. Sea State 4, Frequency 0.4, Angle 60°. Filter for Sea State 9, Frequency 1.5, Angle 120°.

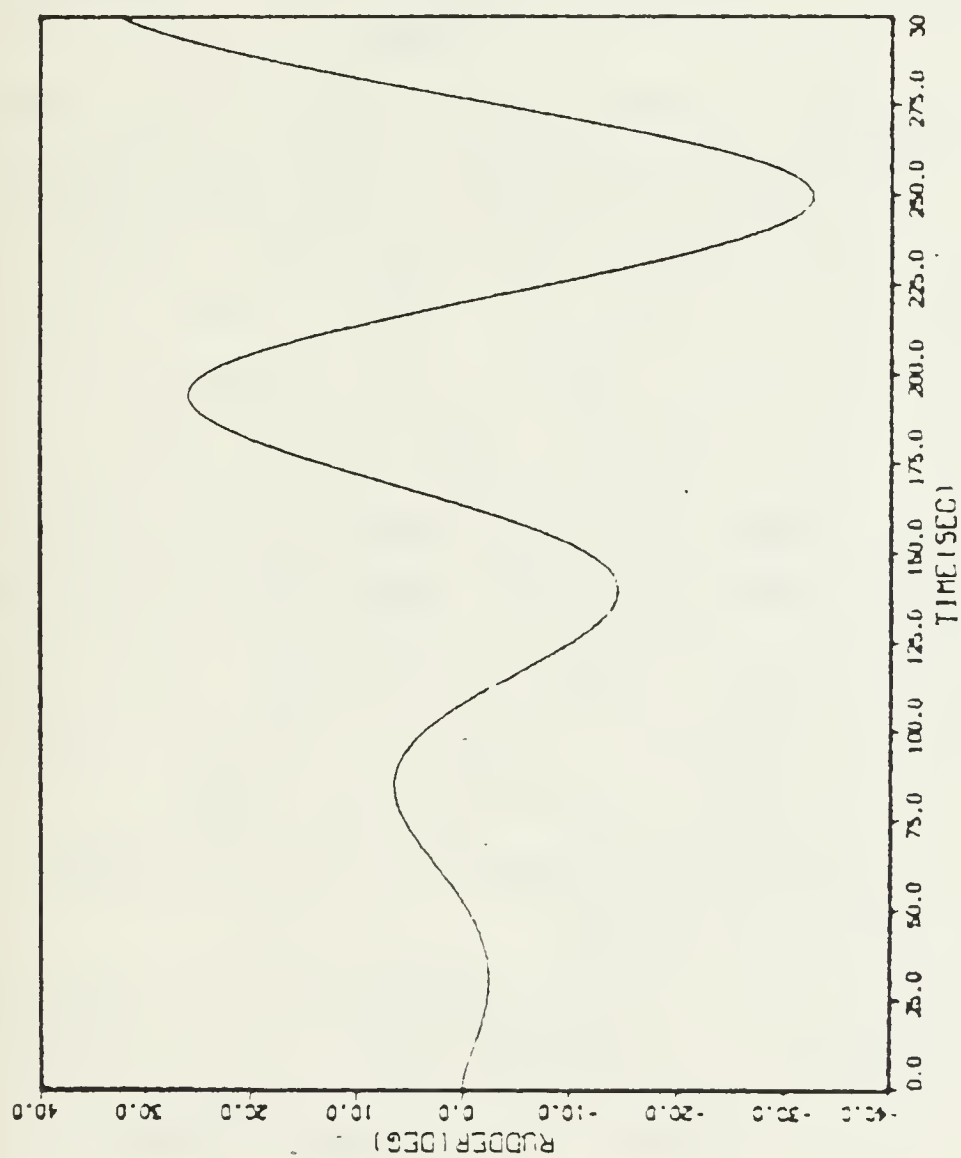


Figure 4.16 Rudder vs Time: Sea 4, Frequency 0.4, Angle 60°. Filter for Sea State 9, Frequency 1.5, Angle 120°.

## V. IRREGULAR SEAS - CONTROLLER DESIGN

The major characteristic of the sea is its irregularity. This irregularity can be described by statistical methods by assuming that a large number of regular (sinusoidal) waves having different wavelengths, directions, phases and amplitudes are superimposed to form the randomly varying sea.

The presence of the irregular sea was obtained by coupling a sea state generator program to the FORTRAN program as is indicated in Appendix D. The sea state generator program generates added mass and added inertia values as function of the encounter frequency and also calculates forces and moments imparted to the shiphull by the sea. The forces and moments are stored in a look up table which was coupled to the equations of motion. The irregular sea waves impinging on the ship contain the total energy density spectrum composed of many frequencies and the ship responds to an average value of added mass and added inertia, while in the regular sea the added mass and added inertia were known for a given encounter frequency. We decided to use values for added mass and added inertia corresponded to encounter frequency 0.75 rads per sec, since the energy density is maximum in the vicinity of this frequency [Ref. 5]. This frequency gave us values representative of an average value for added mass and added inertia.

The controller used for this study was the controller described in Chapter 4 (Figure 4.1). The optimized controller parameters and the cost J for sea states 4, 6, 7, 9 and 0°, 30°, 60°, 90°, 120°, 150°, 180° encounter angles are indicated in Table IX.

Studying the Table IX we can draw the following conclusions:

- For sea states 6, 7, 9, the higher the sea state the higher the cost, for every particular encounter angle.
- Comparing costs for sea states 4 and 6 we discover some anomaly. The cost for a specific encounter angle in sea state 4 is higher than the cost for the same encounter angle in sea state 6. Logically, we expect higher cost for higher sea state.
- The reason for this anomaly may be the method we used in order to obtain the added mass and added inertia values. The average, we consider, might not represent the actual average.

Appendix E provides the computer program necessary to achieve the system's response. Some typical responses are indicated in Figures 5.1, 5.2, 5.3, 5.4.

TABLE IX  
Optimal Controller Parameters for Random Sea

| Sea State 4                 |           |           |           |           |
|-----------------------------|-----------|-----------|-----------|-----------|
| encounter<br>angle(degrees) | K1        | T1        | T2        | J         |
| 0                           | 0.6021814 | 60.30849  | 10.02579  | 0.342E-24 |
| 30                          | 1.5121580 | 89.85324  | 19.85960  | 0.10719   |
| 60                          | 0.6298036 | 79.07199  | 10.29221  | 0.054196  |
| 90                          | 0.6452737 | 82.68692  | 10.79342  | 0.076713  |
| 120                         | 0.7485995 | 85.77544  | 12.37746  | 0.137624  |
| 150                         | 0.9101038 | 92.71379  | 15.21078  | 0.012319  |
| 180                         | 0.6021814 | 60.30849  | 10.02579  | 0.189E-28 |
| Sea State 6                 |           |           |           |           |
| encounter<br>angle(degrees) | K1        | T1        | T2        | J         |
| 0                           | 0.6021814 | 60.30849  | 10.02579  | 0.172E-34 |
| 30                          | 1.8743490 | 61.82320  | 32.22498  | 0.044758  |
| 60                          | 0.8662014 | 90.72922  | 14.44058  | 0.028238  |
| 90                          | 0.7370305 | 84.08502  | 12.17457  | 0.018541  |
| 120                         | 2.6737600 | 138.06650 | 48.52447  | 0.065028  |
| 150                         | 0.4874309 | 77.86977  | 41.73848  | 0.012478  |
| 180                         | 0.6021814 | 60.30849  | 10.02579  | 0.767E-23 |
| Sea State 7                 |           |           |           |           |
| encounter<br>angle(degrees) | K1        | T1        | T2        | J         |
| 0                           | 0.6021814 | 60.30849  | 10.02579  | 0.142E-34 |
| 30                          | 1.7232471 | 66.44597  | 27.32489  | 0.41237   |
| 60                          | 1.8508301 | 91.39410  | 36.91092  | 0.377894  |
| 90                          | 3.7642412 | 62.27244  | 86.58169  | 0.258193  |
| 120                         | 1.8482047 | 99.64923  | 91.28040  | 0.225806  |
| 150                         | 0.8519831 | 67.02328  | 64.96774  | 0.037724  |
| 180                         | 0.6021814 | 60.30849  | 10.02579  | 0.811E-21 |
| Sea State 9                 |           |           |           |           |
| encounter<br>angle(degrees) | K1        | T1        | T2        | J         |
| 0                           | 0.6021814 | 60.30849  | 10.02579  | 0.711E-35 |
| 30                          | 3.1908160 | 138.56101 | 71.44171  | 1.306741  |
| 60                          | 3.0888780 | 152.01630 | 72.66160  | 0.961709  |
| 90                          | 3.2440700 | 121.13566 | 105.98480 | 0.523769  |
| 120                         | 1.5461040 | 111.49130 | 99.64659  | 0.2101076 |
| 150                         | 0.3758357 | 73.88629  | 35.17305  | 0.5007348 |
| 180                         | 0.6021814 | 60.30849  | 10.02579  | 0.121E-31 |



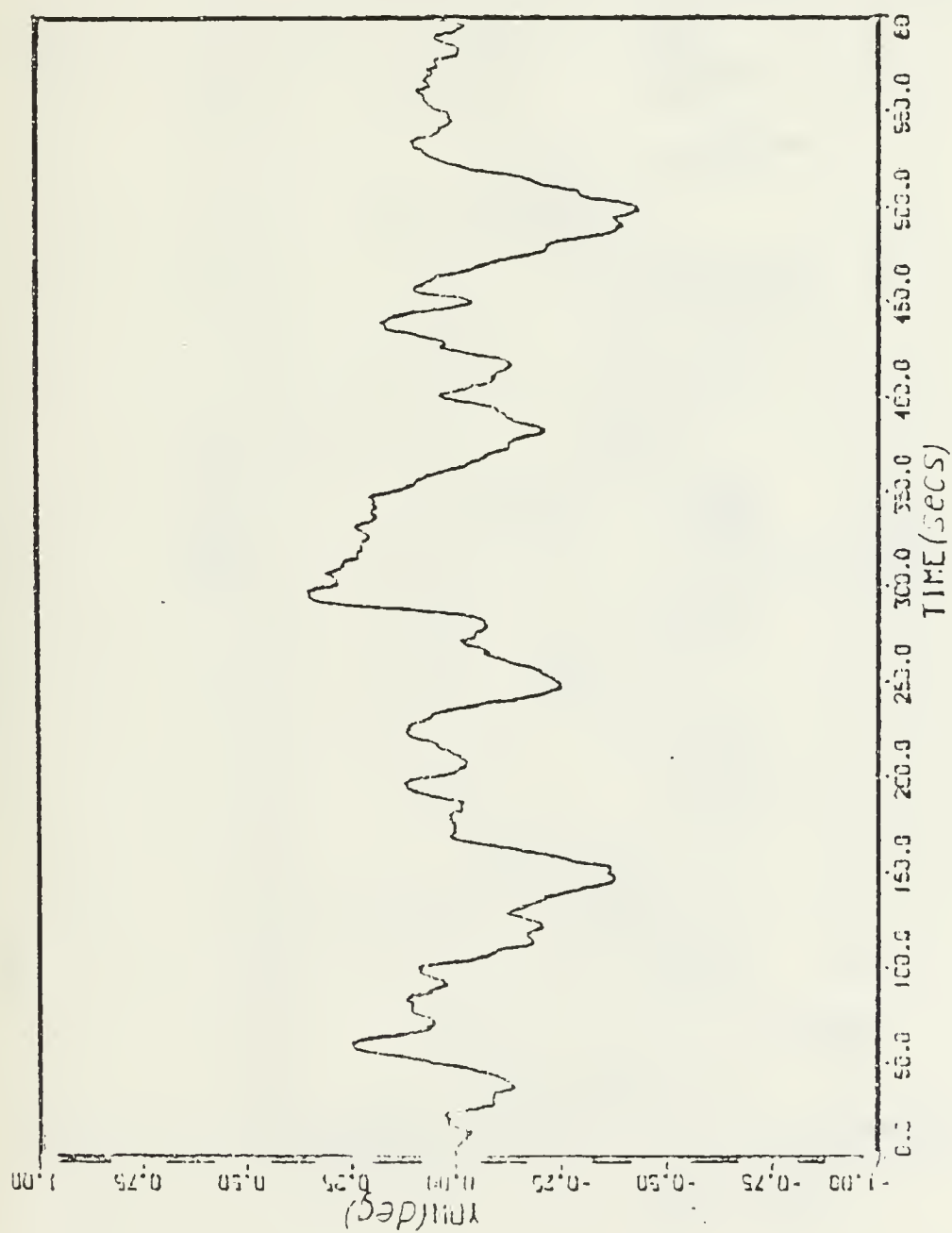


Figure 5.1 Yaw vs Time, Sea state 6.  
Encounter Angle 60°.

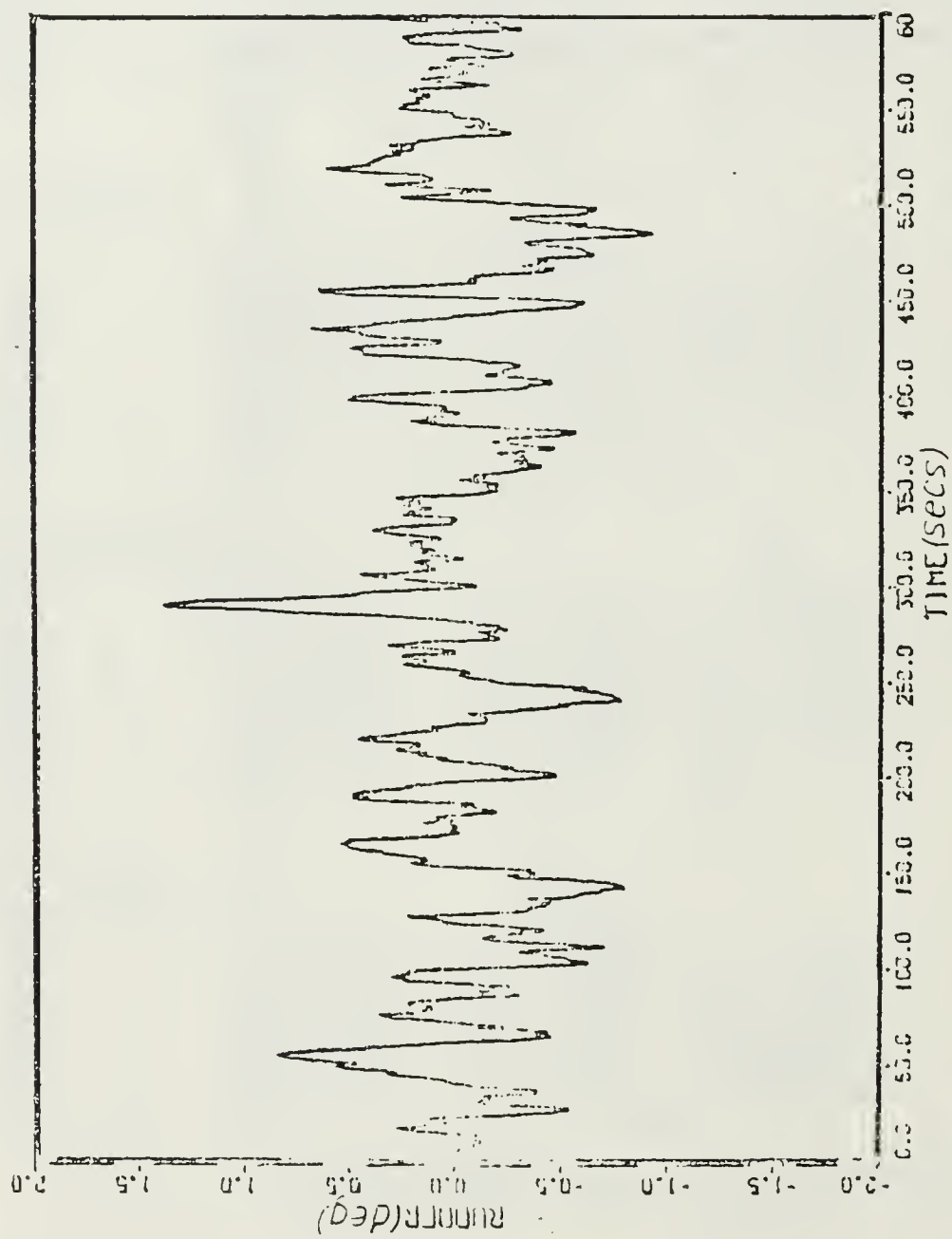


Figure 5.2 Rudder vs Time, Sea State 6.  
Encounter Angle 60°.

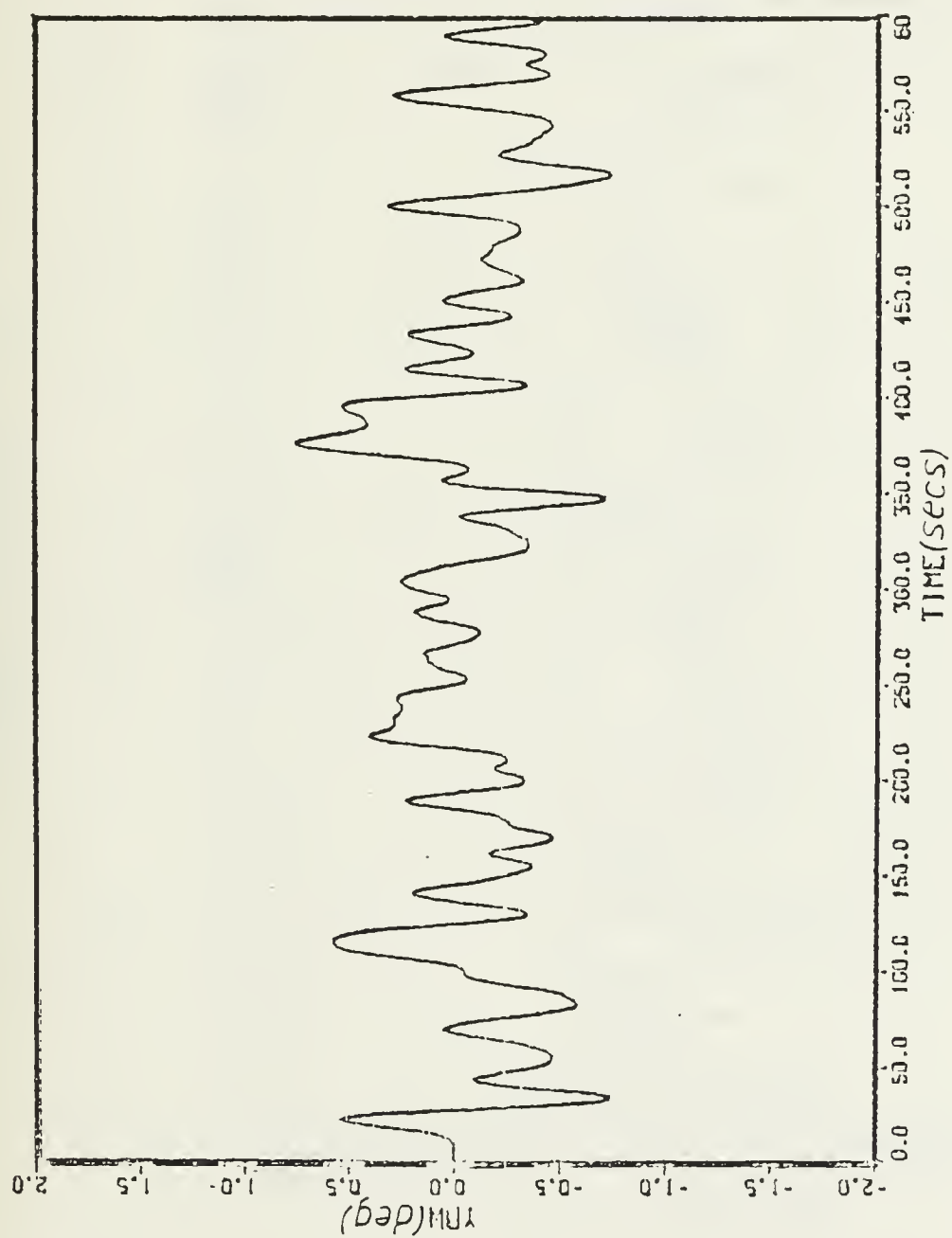


Figure 5.3 Yaw vs Time, Sea State 7.  
Encounter Angle 60°.

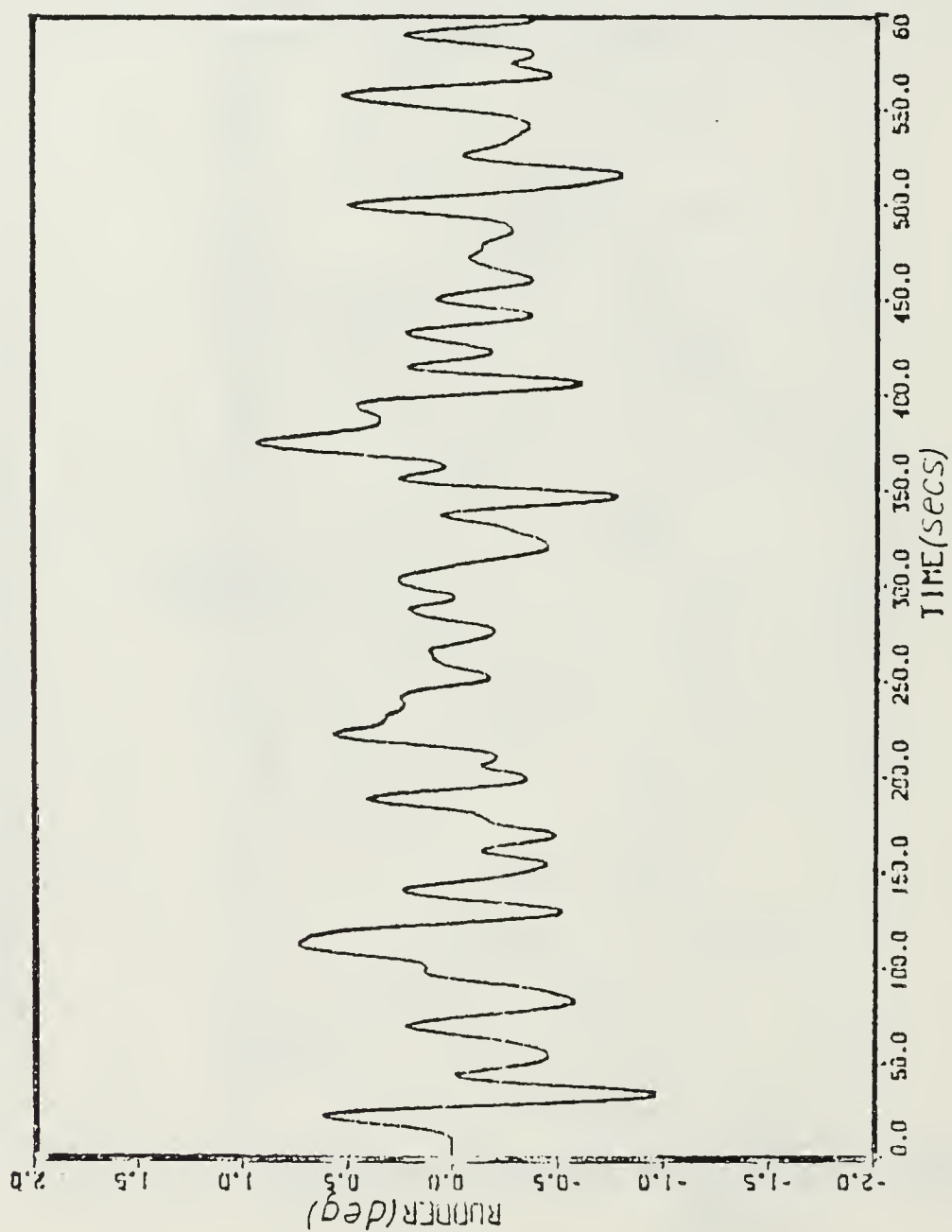


Figure 5.4 Rudder vs Time, Sea State 7.  
Encounter Angle 60°.

## VI. MINIMIZATION SUBROUTINE FOR ONBOARD USE

### A. GENERAL

As is mentioned earlier in Chapter 1 the function minimization subroutine used for these studies was BOXPLX. This subroutine will find the minimum of any function, linear or nonlinear, subject to explicit constraints of the variables or implicit constraints on functions of the variables. It will handle a maximum of 25 variables but can handle up to 50 variables with user modification.

The variables in BOXPLX are allowed to move within a feasible region (n-dimensional space, where n is the number of variables) defined by upper and lower bounds on their values. The choices for upper and lower bounds for the parameters are based on an understanding of the function of each coefficient of the system. Experience indicates that while accurate selections of these bounds are not necessary, intelligent selection of these as well as the starting values (guesses) can considerably reduce the computer number of trials needed for solution convergence. This conclusion was drawn trying to obtain the controller parameters for Tables V, VI, VII, VIII in Chapter 4. The function minimization subroutine, when starting the minimization process with arbitrary chosen guesses, required more than 100 trials for convergence while by choosing guesses close to the optimal parameters required more than 50 and less than 100 trials. Considering that every trial lasted 600 seconds (10 minutes) and the function minimization subroutine requires about 60 samples (trials) before telling us it had found the minimum this would mean 10 hours for the control to adjust itself. For obvious reasons, such operation is not acceptable for on board use.

For obvious reasons, such operation is not acceptable for on board use.

## B. ATTACKING THE PROBLEM

We started to investigate ways to improve this. These efforts include:

- Finding a more efficient function minimization subroutine
- Studying the flatness of the cost surface
- Reducing sampling time

## C. SOLVING THE PROBLEM

Switching to another function minimization subroutine we found that the new one (ZXMWD) suffered from the same disadvantages.

The experiments carried out, more than two hundred, indicated that the cost surface is really flat. The BOXPLX after a few trials started to focus on the minimum but before it converged, it needed more than 50 trials, even if the guesses were close to the optimal. The reason is the way BOXPLX itself tries to find the minimum of a function of NV variables. It converges when the cost FE remains unchanged for  $2 \cdot NV$  consecutive trials with accuracy  $10^{-6}$ . An effort to modify this termination criterion in terms of the consecutive trials was successful. Table X indicates the comparison between modified and unmodified BOXPLX, for sea state 6, encounter frequency 1.5 rads per sec and encounter angle  $120^\circ$ . As we can observe in Table X the cost in each case remains almost the same while the trials required for convergence are dependent on the guesses made and the termination criterion established.

The value of the cost is in general the summation of incremental contributions for each integration step and is



TABLE X  
First Modification in BOXPLX

| BOXPLX     | Guesses   | Trials | Termination<br>Criterion | Cost       |
|------------|-----------|--------|--------------------------|------------|
| Unmodified | Arbitrary | 100    | 6                        | 0.01146720 |
| Unmodified | Optimal   | 72     | 6                        | 0.01146720 |
| Modified   | Arbitrary | 42     | 3                        | 0.01146812 |
| Modified   | Optimal   | 11     | 3                        | 0.01146720 |
| Modified   | Arbitrary | 7      | 2                        | 0.01157926 |
| Modified   | Optimal   | 1      | 2                        | 0.01146720 |

therefore dependent on the total time of the simulation. This is important in that the optimal gain coefficients arrived at in this manner are not optimal for steady-state performance but only for the time frame covered. This should be adequate provided the time frame selected is long relative to the time required for the initial condition response to die out. This is the reason Reid has chosen time frame 600 seconds [Ref. 1,2]. Of course this time period is large and we expect steady-state behaviour faster than 10 minutes. Simulation studies indicate that the ship, controlled by the controller described in Figure 4.1, reaches the steady-state situation in less than 100 seconds. So, we can reduce the 600 seconds time frame to 200 seconds, safely. This is very important since now the modified function minimization subroutine BOXPLX, uses samples of 200 seconds long instead of 600 seconds, converges in less than 30 minutes which is reasonable for on board use. Since the value of the cost is dependent on the time frame taken we expect reduced cost for 200 seconds samples long, in any case.

As we discussed earlier the BOXPLX compares the consecutive trials with accuracy  $10^{-6}$ . Since we do not need so big accuracy a second modification is necessary. We decided to change the existing accuracy to  $10^{-4}$ .

Table XI indicates the trials required for BOXPLX convergence, after the second and last modification, for sea

TABLE XI  
Second Modification in BOXPLX

| Guesses   | Trials | Termination<br>criterion | Cost        |
|-----------|--------|--------------------------|-------------|
| Arbitrary | 17     | 3                        | 0.003999837 |
| Optimal   | 8      | 3                        | 0.003995277 |
| Arbitrary | 5      | 2                        | 0.004024354 |
| Optimal   | 1      | 2                        | 0.003995247 |

state 6, encounter frequency 1.5 rads per sec and encounter angle  $120^\circ$ . By comparing Tables X and XI we can see the further improvement for the function minimization subroutine convergence. The difference in the cost is due to the different time frames used. The modified function minimization subroutine BOXPLX is indicated in Appendix F.

## VII. ADAPTIVE CONTROL

### A. NECESSITY OF ADAPTIVITY

The plant, the system which is supposed to be controlled, is normally exposed to a time varying environment. The ship's speed, the wave encounter angle and the sea state are changing drastically during the seaway. Since changes encountered are not completely predictable an optimum preprogrammed time-varying controller is not possible.

If we assume-and it is apparent from the previous discussion in this study-that no feasible fixed parameter controller provides acceptable response over the entire performance spectrum, it is necessary that some means is provided for adjusting controller parameters according to the sea conditions and ship's operational characteristics. Adaptive control is thus an effort to extend basic optimum control concepts to these studies.

### B. CANDIDATE ADAPTIVE SCHEMES

Since we are looking for 1% or 2% savings in fuel cost, we have to feed the system with precise information. Exact knowledge of the sea state, the wave encounter angle and the ship's ground speed is vital for this purpose. Currently the Navy is involved in a program that will provide precision navigation data. Garcia [Ref. 5], provides very good information on this subject.

An adaptive control scheme is indicated in Figure 7.1. Once the adaptive part of the scheme is set up the sea state, encounter wave angle and ship's speed are fed to the filters box by the appropriate sensors. The filters box

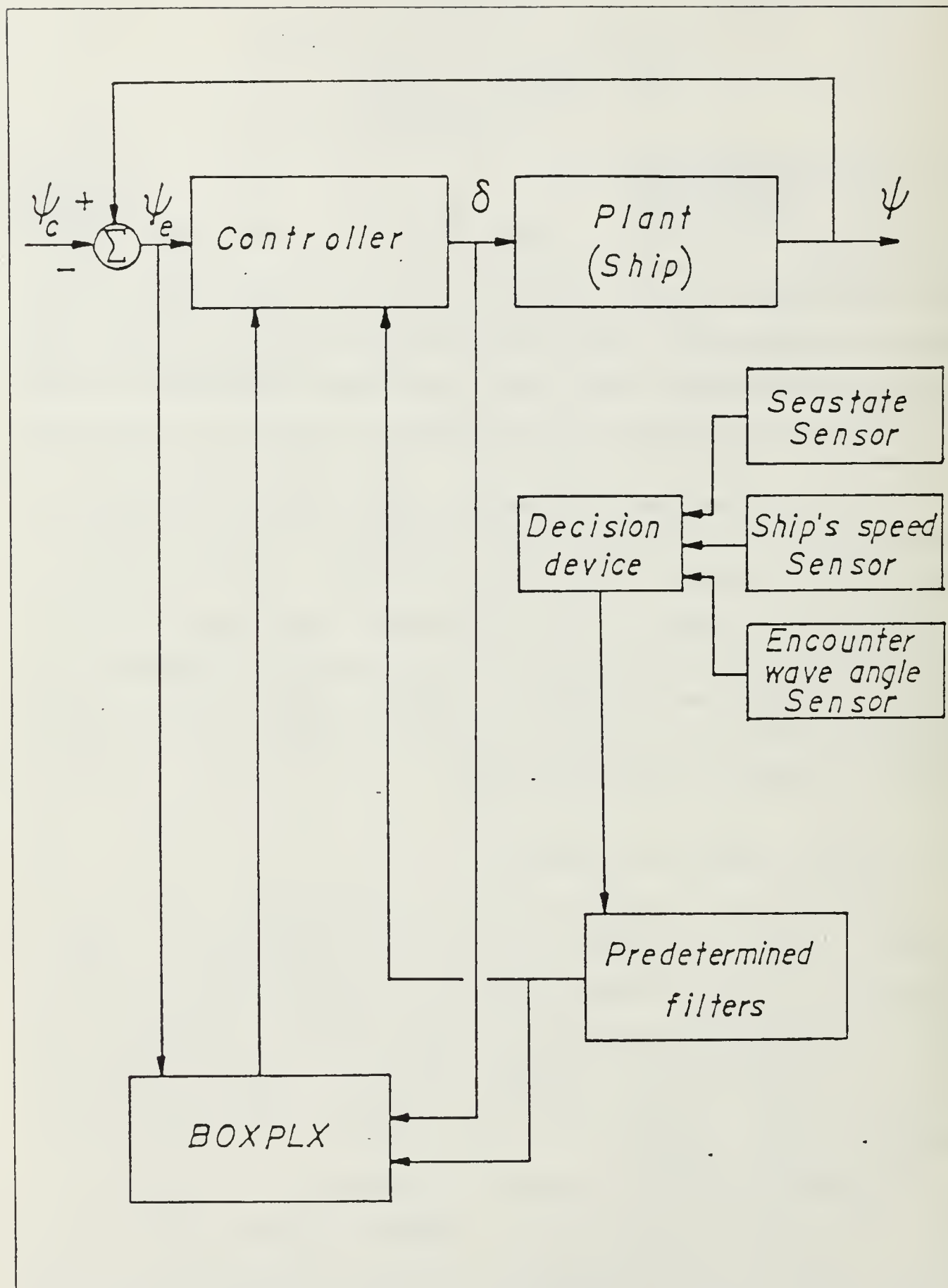


Figure 7.1 Adaptive Control Scheme

includes predetermined optimal filter sets for different discrete sea states, wave angles and ship's speed. Actually, it is a look up table similar to those of Tables V, VI, VII and VIII. The output of the filter's box is a filter which corresponds to discrete conditions close to those fed by the sensors. The function minimization subroutine accepting the rudder angle, yaw error and the predetermined filter set as initial guesses tries to obtain the optimal filter for the exact sea state, wave encounter angle and ship's speed. At the same time the plant is controlled by the controller with the optimal predetermined set of parameters for conditions close to the actual. When the function minimization subroutine reaches the minimum, it supplies the controller with a new set of parameters which is the optimal set for the present conditions.

But, what happens if either some or all the sensors provide new inputs to the system? A decision device placed after the sensors decides whether or not the change is appreciable. This device compares the current conditions with those used to obtain the controller which currently governs the system. If the change is higher than some desired percentage then a new predetermined filter is passed to the controller and the function minimization subroutine tries to find the optimal controller parameters for the new situation.

From the scheme of Figure 7.1 we can eliminate the predetermined filters device which provides a less expensive system. In this case the function minimization subroutine will need a much longer time to determine the optimal filter for rapid changes in course and speed, even if we assume that rapid changes in sea state don't occur. Finally, the function minimization subroutine might work continually "on line" as is indicated in Figure 7.2. In this scheme a new controller set is obtained in every subroutine iteration and

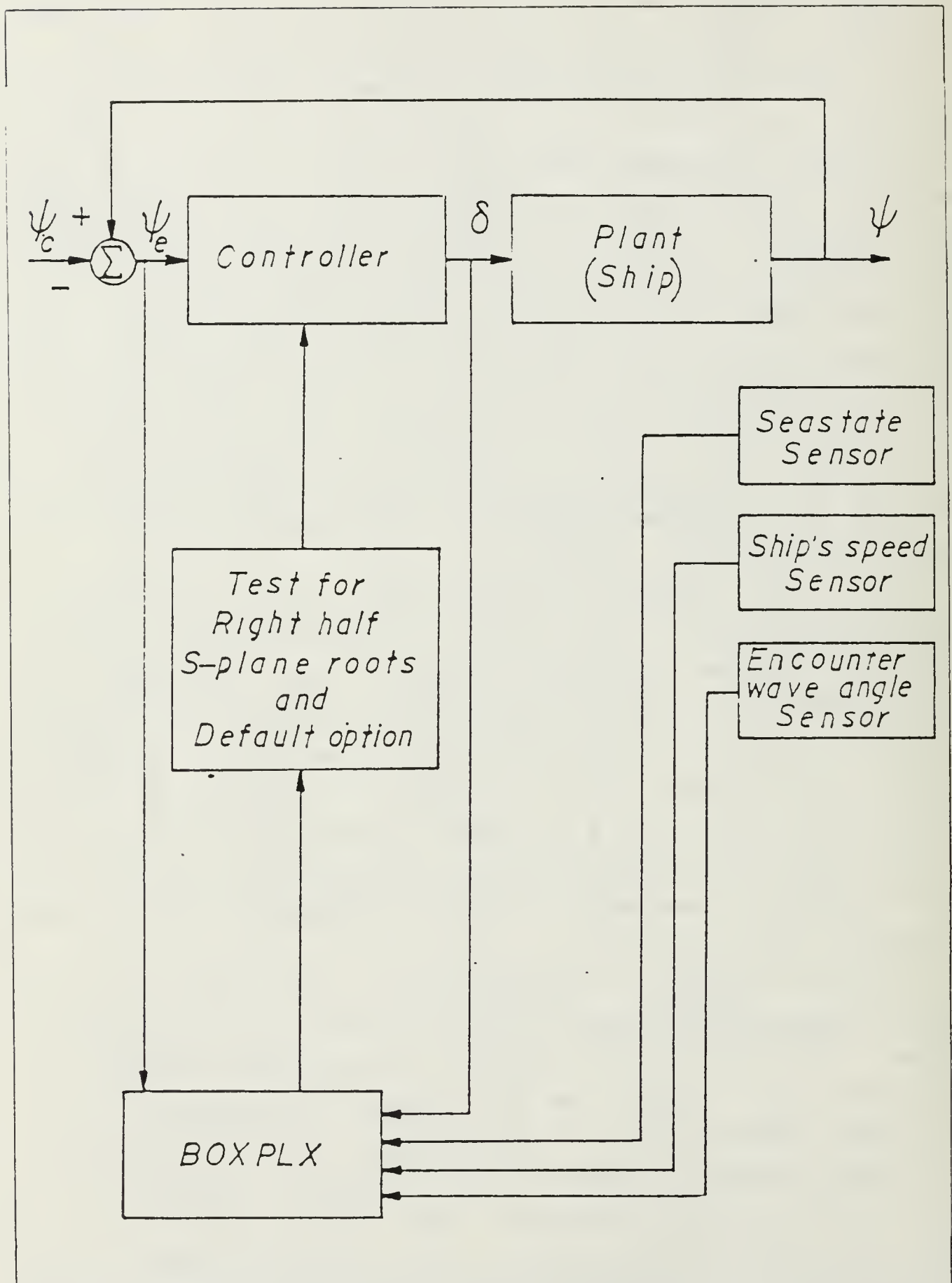


Figure 7.2 On Line Adaptive Scheme



some constraints for the controller parameters are necessary in order to avoid operation in unstable regions. Thus, the filter supplied by the subroutine for controlling the plant must be tested for characteristic equation roots in the right half S-plane. In that case a default option must exist, and a special device for such purposes is necessary. This device will permit change in the filter parameters only when the new set still keeps the system in a stable situation.

Whichever adaptive scheme we adopt, we must provide for manual operation for the system. Manual operation will be desired in the following cases:

- Arriving ports
- Leaving ports
- Restricted waters
- Avoid collision in open seas
- Computer down

For the first two situations, since we usually expect no heavy seas, the optimal filter for sea state 1 seems to be more suitable. Also, this filter can serve as initial condition for the adaptive schemes described before, when we are leaving ports. For the rest of the situations the last operating optimal filter is the most appropriate.

## VIII. CONCLUSIONS AND RECOMMENDATIONS

### A. CONCLUSIONS

The principal conclusions from this study of the SL-7 containership as they related to steering may be stated as follows:

- It is evident that a control system which provides the ship heading and simultaneously reduces the propulsive losses does exist and therefore such a controller saves fuel. We can't conclude how much the savings are, since there is no reference for comparison between the conventional autopilot and the autopilot which, in addition, holds the potential for reducing the propulsive losses. The literature says that savings 1% or 2% is possible.
- An adaptive controller, that minimizes propulsion losses as ship characteristics and environmental conditions change, may be designed using a self-optimizing technique employing a suitable performance criterion.
- Studying every particular situation we conclude that the cost surface is flat and therefore accurate determination of the controller parameters is not required. So, if we decide to use the adaptive control scheme of Figure 7.1 we don't have to store every particular filter in the look up table since one filter may be suitable for different ship characteristics and sea conditions.
- The weighting factor  $\lambda$  used in the performance criterion equation 3.5 plays an exceptional and important role in the optimal controller parameters determination. However, it is obtained from studies based on

many assumptions and therefore isn't predicted accurately. As a consequence the controller found does not minimize added resistance unless the proper value of the weighting factor  $\lambda$  has been used.

- The method used to obtain the average for the added mass and added inertia for the irregular seas studies might not represent the actual average.
- The function minimization subroutine BOXPLX after two modifications seems to be pretty suitable for on board use working as a main part of the adaptive scheme.

## B. RECOMMENDATIONS FOR FUTURE STUDIES

The following recommendations for future work to gain a fuller and deeper understanding of the problem are made as follows:

- Some studies are necessary in order to investigate why part of the obtained controllers in Tables V, VI, VII, VIII are lag and part of them are lead filters.
- As we stated in chapter 4 the yaw and rudder excursions in Figures 4.2 through 4.9 are less than  $1^\circ$ . It is necessary to investigate the reason for that. It might be because of the optimization of the filter or the forces and moments have not been sealed properly.
- It is necessary to find out the appropriate average values for the added mass and added inertia before we attempt further studies in irregular seas.
- The full hydrodynamic coefficients for the SL-7 are necessary in order to develop and include the surge equation in our ship model. So far we ignore the surge equation and we assumed constant ship speed while in reality the added resistance due to steering must reduce the ship speed.

- By developing the surge equation in our ship model we may be able to determine a good value for the weighting factor to be used in the performance criterion.
- Also, with the surge equation available in our model we should be able to calculate actual energy losses and savings in fuel.
- As we stated in chapter 6 the time frames (samples) used by the BOXPLX must be long relative to the time required for the initial condition response to die out. Reid [Ref. 1,2] has chosen time frame 600 seconds long. This time frame is long and it is necessary to find out the sufficient time frame since the time required by the function minimization subroutine for convergence is directly proportional to the sample duration.

APPENDIX A  
NOMOTO THIRD ORDER MODEL DETERMINATION

```
//NOMOTO JOB (XXXX,XXXX), 'RESEARCH', CLASS=J
//*MAIN ORG=NPGVM1.XXXXP
// EXEC FORTXCG, PARM.FORT='OPT(2)', IMSL=DP, REGION=1024K
//FORT.SYSIN DD *
C  IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
C  OBTAINED CHANGE XS(*) TO X(*) AND DELETE XU(*), AND XL(*)
      DIMENSION XS(4), XU(4), XL(4)
      XS(1)=0.1
      XS(2)=15.13
      XS(3)=15.675
      XS(4)=9.014
C  XS(I) IS THE STARTING GUESS
C  XL(I) IS THE LOWER LIMIT FOR THE I'TH VARIABLE
C  XU(I) IS THE UPPER LIMIT FOR THE I'TH VARIABLE
      XL(1)=.01
      XU(1)=1.0
      XL(2)=1.0
      XU(2)=20.
      XL(3)=1.0
      XU(3)=100.
      XL(4)=1.0
      XU(4)=100.0
C  A DESCRIPTION OF THE FOLLOWING PARAMETERS
C  IS DISCUSSED IN BOXPLX
      R=9./13.
      NTA=1000
      NPR=0
      NAV=0
      NV=4
      IP=0
```

```

C THE FOLLOWING STATEMENT MUST BE CHANGED TO
C CALL PLANT(XX)
C IF ONLY SIMULATION IS WANTED
    CALL BOXPLX(NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)
    WRITE (6,25)
25  FORMAT(1X,' OPTIMAL GAINS',/)
    DO 30 I=1,4
30  WRITE(6,40)I,XS(I)
40  FORMAT(1X,'X(',I2,')=' ,F14.7)
    WRITE (6,77) TDIFF
77  FORMAT(1X,'COST=' ,F14.7)
    STOP
    END
C SUBROUTINE PLANT(XX) SIMULATES THE SHIP
  SUBROUTINE PLANT(XX)
    COMMON TDIFF
    REAL*8 L,L2,L3,L4,L5,L6,RXR,RXI,RYR,RYI,MZR,MZI,RX,RY
    REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT,TX,TY
    REAL*8 TIME,ETIME,XUDOT,XU,XUU,XVR,XVV,XDD,WA,WE,RZ
    REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT,TZ
    REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
    REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT
    REAL*8 YAWC,D2,D
    REAL*8 K,TP1,TP2,Z,X1,X2,X3,X4,X5,YAW2,S
    DIMENSION XX(4)
C INITIAL CONDITIONS FOR INTEGRATION
C SIMULATION END TIME IN SECONDS
    ETIME=600.
    TIME=0.0
    ICOUNT=1
C INITIALIZE THE COST FUNCTION
    TDIFF=0.0
C GAIN COEFFICIENTS TO BE OPTIMIZED
    K=XX(1)
    Z=XX(2)

```



```

      TP1=XX(3)
      TP2=XX(4)
C   X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
      X=0.0
      Y=0.0
      XDOT=0.0
      YDOT=0.0
C   U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
      V=0.0
      UDOT=0.0
      VDOT=0.0
      YAW=0.0
      R=0.0
      RDOT=0.0
C   ORDERED SPEED IN FEET/SEC
C   38.81 FT/SEC=23 KNOTS
      UC=38.81
C   AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
      U=UC
C   D = RUDDER ANGLE
      D=0.0
      L=880.5
      L2=L**2
      L3=L*L*L
      L4=L*L3
      L5=L*L4
      L6=L*L5
C   SEA DISTURBANCE
C   FORCES IN X,Y DIRECTION COMPUTED IN FORCES
C   MOMENTS IN Z
      FX=0.0
      FY=0.0
      MZ=0.0
C   RXR=-.15744D+05
C   RXI=-.19950D+06

```

```

C      RYR=0.52365D+04
C      RYI=0.18699D+06
C      MZR=-.29870D+08
C      MZI=-.37751D+07
      RXR=-.50230D+04
      RXI=0.12712D+05
      RYR=0.35290D+04
      RYI=-.31909D+05
      MZR=0.38826D+07
      MZI=-.64313D+07
C      RXR=0.28540D+04
C      RXI=-.99574D+04
C      RYR=-.85441D+04
C      RYI=0.39595D+05
C      MZR=-.13014D+08
C      MZI=0.11348D+08
C      RXR=-.75642D+04
C      RXI=0.83497D+04
C      RYR=0.23379D+05
C      RYI=-.81502D+05
C      MZR=0.28622D+07
C      MZI=-.19388D+08
C      RXR=-.37916D+04
C      RXI=0.16381D+04
C      RYR=-.76647D+05
C      RYI=-.37685D+05
C      MZR=-.83915D+07
C      MZI=-.53176D+07
      RX=DSQRT(RXR**2+RXI**2)
      RY=DSQRT(RYR**2+RYI**2)
      RZ=DSQRT(MZR**2+MZI**2)
      TX=DATAN2(RXI,RXR)
      TY=DATAN2(RYI,RYR)
      TZ=DATAN2(MZI,MZR)
C      SIGNIFICANT WAVE HEIGHT; SEA STATE 1-0.32,2-0.75,3-2.5,

```

```

C 4-5.0,5-7.0,6-10.0,7-17.5,8-20.5,9-27.0
    WA=10.0
C ENCOUNTER FREQUENCY .1,.2,.3,.4,.5,.6,.75,1.0,1.5,2.5
    WE=0.4
C HYDRODYNAMIC COEFFICIENTS ARE INSERTED AS PARAMETERS
    RHO=1.9876
    MASS=(.0044)*(.5*RHO*L3)
    IZ=(0.00028)*(.5*RHO*L5)
    YAWE=0.0
    X1=0.0
    X2=0.0
    X3=0.0
    X4=0.0
    X5=0.0
    YAW2=0.0
200 CONTINUE
    S=DSQRT(U**2 + V**2)
C INPUT YAW COMMAND
    YAWC=0.0
    IF (TIME.GE.0.0) YAWC=(1.0/57.296)
C ERROR SIGNAL TO DRIVE RUDDER (YAW ACTUAL - YAW COMMAND)
C FOR EQUATIONS OF MOTION.
    YAWE=YAW - YAWC
    D=YAWE
C
C NOMOTO 3RD ORDER PLANT
C
C ERROR SIGNAL TO DRIVE RUDDER (YAW COMMAND - YAW ACTUAL)
C FOR NOMOTO MODEL.
    D2=YAWC-YAW2
    X1=(D2-X2)/TP1
    X3=K*(Z*X1+X2)
    X4=(X3-X5)/TP2
C AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
    XUDOT=(-.0001)*(.5*RHO*L3)

```

```

XUU=(-0.0003)*(0.5*RHO*L2)
XU=(-0.0253)*(0.5*RHO*L2*S)
XVR=(0.0039)*(0.5*RHO*L3)
XVV=(-0.0012)*(0.5*RHO*L2)
XDD=(-0.0005)*(0.5*RHO*L2*S**2)
C  LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
C  YV=(-0.00758)*(0.5*RHO*L2*S)
    YR=(0.0023)*(0.5*RHO*L3*S)
    YD=(0.00145)*(0.5*RHO*L2*S**2)
    YVVR=(0.01)*(0.5*RHO*L3/S)
    YVRR=(-0.008)*(0.5*RHO*L4/S)
    YVVV=(-0.03)*(0.5*RHO*L2/S)
    YRRR=(0.003)*(0.5*RHO*L5/S)
    YDDD=(-0.0005)*(0.5*RHO*L2*S**2)
    YVDOT=-0.30908D+07
    YV=-0.81271D+04
C  YVDOT=-.36185D+07
C  YV=-.24757D+06
C  YVDOT=-.32890D+07
C  YV=-.11775D+07
C  YVDOT=-.23038D+07
C  YV=-.18267D+07
C  YVDOT=-.59800D+06
C  YV=-.13260D+07
C  MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
    NV=(-0.00213)*(0.5*RHO*L3*S)
C  NR=(-0.00105)*(0.5*RHO*L4*S)
    ND=(-0.0007)*(0.5*RHO*L3*S**2)
    NVVR=(-0.015)*(0.5*RHO*L4/S)
    NVRR=(-0.008)*(0.5*RHO*L5/S)
    NVVV=(0.01)*(0.5*RHO*L3/S)
    NRRR=(-0.006)*(0.5*RHO*L6/S)
    NDDD=(0.0001)*(0.5*RHO*L3*S**2)
C  NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE, SPEED, ENCOUNTER FREQUENCY

```

```

C
C      NRDOT=(-0.00027)*(.5*RHO*L5)
C      SPEED=23 KNOTS, ENCOUNTER ANGLE = 60, ENCOUNTER FREQ=0.75
C      NRDOT=-.26251D+12
C      NR=-.53637D+09
C      NRDOT=-.20125D+12
C      NR=-.94970D+10
C      NRDOT=-.18671D+12
C      NR=-.46860D+11
C      NRDOT=-.14518D+12
C      NR=-.87538D+11
C      NRDOT=-.37261D+11
C      NR=-.69856D+11
C      SETS SEA STATE TO ZERO
C      FX=0.
C      FY=0.
C      MZ=0.
C      FX=WA*RX*DCOS(WE*TIME+TX)
C      FY=WA*RY*DCOS(WE*TIME+TY)
C      MZ=WA*RZ*DCOS(WE*TIME+TZ)
C      U ACTUAL SPEED
C      UC COMMANDED SPEED
C      XP = PROPELLER THRUST
C      XP=-XUU*UC**2
C      EQUATIONS OF MOTION
C      UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C      1 + XDD*D*D + FX + XP )/(MASS-XUDOT)
C      VDOT=(YV*V + (YR-MASS*U)*R + YD*D + YVVR*V**2*R
C      1 + YVRR*V*R**2 + YVVV*V*V**3
C      2 + YRRR*R**3 + YDDD*D**3 + FY )/(MASS-YVDOT)
C      RDOT=(NV*V + NR*R + ND*D + NVVR*V**2*R + NVRR*V*R**2
C      1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3 + MZ )/(IZ-NRDOT)
C      WHEN TO PRINTOUT
C      IF (ICOUNT.EQ.11) GO TO 50
C      GO TO 300

```

```

C  CONVERT RADIANS TO DEGREES
50  YAWDEG= YAW*57.296
    RDEG=R*57.296
    RDDEG=RDOT*57.296
    DDEG=D*57.296
    YAWC=YAWC*57.296
    ICOUNT=1
C  TEST IF WANT TO STOP
300  IF (TIME.GE.ETIME) GO TO 400
C  INTEGRATION STEP SIZE DELT
    DELT=1.0
C  INTEGRATION
    X2=X2+X1*DELT
    X5=X5+X4*DELT
    YAW2=YAW2+X5*DELT
    U=U+UDOT*DELT
    V=V+VDOT*DELT
    R=R+RDOT*DELT
    YAW=YAW+R*DELT
C  CONVERT SHIP TO FIXED COORDINATES ON EARTH
    XDOT=U*DCOS(YAW)-V*DSIN(YAW)
    YDOT=U*DSIN(YAW)+V*DCOS(YAW)
    X=X+XDOT*DELT
    Y=Y+YDOT*DELT
    TIME=TIME+DELT
    ICOUNT=ICOUNT+1
C  COST FUNCTION
    TDIFF=TDIFF+ (YAW-YAW2)**2
    GO TO 200
400  CONTINUE
C  WRITE(6,500) TDIFF,K,Z,TP1,TP2
500  FORMAT(' ',1X,' COST =',F12.7,2X,' K =',F10.7,
1  ' Z =',F15.7,' TP1 =',F15.7,2X,' TP2 =',F15.7)
    RETURN
    END

```



APPENDIX B  
REGULAR SEASTATE FORMULATION

```
//REGUGAINS JOB (XXXX,XXXX), 'RESEARCH', CLASS=C
//*MAIN ORG=NPGVM1.XXXXP
// EXEC FORTXCG, PARM.FORT='OPT(2)', IMSL=DP, REGION=1024K
//FORT.SYSIN DD *
C IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
C OBTAINED CHANGE XS(*) TO X(*) AND DELETE XU(*), AND XL(*)
      DIMENSION XS(3), XU(3), XL(3)
      XS(1)=0.9650610
      XS(2)=0.4500911
      XS(3)=5.6194260
C XS(I) IS THE STARTING GUESS
C XL(I) IS THE LOWER LIMIT FOR THE I'TH VARIABLE
C XU(I) IS THE UPPER LIMIT FOR THE I'TH VARIABLE
      XL(1)=0.1
      XU(1)=4.0
      XL(2)=0.1
      XU(2)=15.0
      XL(3)=1.0
      XU(3)=25.0
C A DESCRIPTION OF THE FOLLOWING PARAMETERS
C IS DISCUSSED IN BOXPLX
      R=9./13.
      NTA=1000
      NPR=100
      NAV=0
      NV=3
      IP=0
C THE FOLLOWING STATEMENT MUST BE CHANGED TO
C CALL PLANT(X)
C IF ONLY SIMULATION IS WANTED
```

```

        CALL BOXPLX(NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)
        WRITE (6,25)
25      FORMAT(1X,' OPTIMAL GAINS ',/)
        DO 30 I=1,3
30      WRITE(6,40)I,XS(I)
40      FORMAT(1X,'X(',I2,')=' ,F14.7)
        STOP
        END
        SUBROUTINE PLANT(XX)
C  SUBROUTINE PLANT(XX) SIMULATES THE SHIP
        COMMON TDIFF
        REAL*8 L,L2,L3,L4,L5,L6
        REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
        REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
        REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT
        REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
        REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT,MZI,WA,WE
        REAL*8 DYAW,YAWE,YAWC,ISE,ISR,LAMDA,D,RYR,RYI,MZR
        REAL*8 K1,T1,T2,D,X2,DX2,S,RX,RY,RZ,TX,TY,TZ,RXR,RXI
        DIMENSION XX(3)
C
C  CLOSE LOOP ANALYSIS WITH FILTER
C
C  INITIAL CONDITIONS FOR INTEGRATION
C  SIMULATION END TIME IN SECONDS
        ETIME=600.0
        TIME=0.0
        ICOUNT=1
C  INITIALIZE THE COST FUNCTION
        ISE=0.0
        ISR=0.0
        TDIFF=0.0
        LAMDA=8.128
C  GAIN COEFFICIENTS TO BE OPTIMIZED
        K1=XX(1)

```

```

      T1=XX(2)
      T2=XX(3)
C      WRITE(6,1010) K1,T1,T2
C1010  FORMAT(1X,'K1 =',F15.7,' T1 =',F15.7,' T2 =',F15.7)
C  X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
      X=0.0
      Y=0.0
      XDOT=0.0
      YDOT=0.0
C  U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
      V=0.0
      UDOT=0.0
      VDOT=0.0
      YAW=0.0
      R=0.0
      RDOT=0.0
C  ORDERED SPEED IN FEET/SEC
C  38.81 FT/SEC=23 KNOTS
      UC=38.81
C  AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
      U=UC
C  D = RUDDER ANGLE
      D=0.0
      L=880.5
      L2=L**2
      L3=L*L*L
      L4=L*L3
      L5=L*L4
      L6=L*L5
C  SEA DISTURBANCE
C  FORCES IN X,Y DIRECTION COMPUTED IN FORCES
C  MOMENTS IN Z
      FX=0.
      FY=0.
      MZ=0.

```

```

C      RXR=-0.91037D+03
C      RXI=0.50869D+05
C      RYR=-0.20256D+04
C      RYI=0.18077D+06
C      MZR=-.14310D+08
C      MZI=-.16903D+07
C      RXR=-0.99047D+04
C      RXI=.15994D+06
C      RYR=-.64455D+05
C      RYI=0.61873D+06
C      MZR=.120180+08
C      MZI=-.49204D+07
C      RXR=-0.32876D+05
C      RXI=0.25844D+06
C      RYR=-.27053D+06
C      RYI=.90191D+06
C      MZR=0.11964D+09
C      MZI=0.24103D+08
C      RXR=-.54639D+05
C      RXI=.28236D+06
C      RYR=-.28668D+06
C      RYI=0.79670D+06
C      MZR=0.19925D+09
C      MZI=0.77746D+08
C      RXR=0.27268D+05
C      RXI=-.71601D+05
C      RYR=0.14077D+05
C      RYI=-.28679D+06
C      MZR=-.30892D+08
C      MZI=-.53246D+08
C      RX=DSQRT(RXR**2+RXI**2)
C      RY=DSQRT(RYR**2+RYI**2)
C      RZ=DSQRT(MZR**2+MZI**2)
C      TX=DATAN2(RXI,RXR)
C      TY=DATAN2(RYI,RYR)

```

```

      TZ=DATAN2(MZI,MZR)
C  SIGNIFICANT WAVE HEIGHT; SEA STATE 1-0.32,2-0.75,3-2.5,
C  4-5.0,5-7.0,6-10.0,7-17.5,8-20.5,9-27.0
      WA=10.0
C  ENCOUNTER FREQUENCY .1,.2,.3,.4,.5,.6,.75,1.0,1.5,2.5
      WE=1.5
C  HYDRODYNAMIC COEFFICIENTS ARE INSERTED AS PARAMETERS
      RHO=1.9876
      MASS=(.0044)*(.5*RHO*L3)
      IZ=(0.00028)*(.5*RHO*L5)
      YAWE=0.0
      X2=0.0
      DX2=0.0
200 CONTINUE
      S=DSQRT(U**2+V**2)
C  INPUT YAW COMMAND
      YAWC=0.0
      IF (TIME.GE.0.0) YAWC=0.0
C  ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL - YAW ORDERED)
C  ( COMPENSATOR FILTER )
      YAWE=YAW - YAWC
      DX2=(YAWE-X2)/T2
      D=K1*(T1*DX2+X2)
C  AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C  XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C  DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER FREQUENCY
C
      XUDOT=(-.0001)*(.5*RHO*L3)
      XU=(-0.0253)*(.5*RHO*L2*S)
      XUU=(-0.0003)*(.5*RHO*L2)
      XVR=(0.0039)*(.5*RHO*L3)
      XVV=(-.0012)*(.5*RHO*L2)
      XDD=(-0.0005)*(.5*RHO*L2*S**2)
C  LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
C  YV=(-0.00758)*(.5*RHO*L2*S)

```

```

YR=(0.0023)*( .5*RHO*L3*S)
YD=(0.00145)*( .5*RHO*L2*S**2)
YVVR=(0.01)*( .5*RHO*L3/S)
YVRR=(-0.008)*( .5*RHO*L4/S)
YVVV=(-0.03)*( .5*RHO*L2/S)
YRRR=(0.003)*( .5*RHO*L5/S)
YDDD=(-0.0005)*( .5*RHO*L2*S**2)
C  YUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C  DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER FREQUENCY
C
C  YVDOT=(-0.0039)*( .5*RHO*L3)
C  SPEED=23 KNOTS,ENCOUNTER ANGLE=60,ENCOUNTER FREQ=0.75
C  YVDOT=-.30908D+07
C  YV=-.81271D+04
C  YVDOT=-.36185D+07
C  YV=-.24757D+06
C  YVDOT=-.32890D+07
C  YV=-.11775D+07
C  YVDOT=-.23038D+07
C  YV=-.18267D+07
C  YVDOT=-.59800D+06
C  YV=-.13260D+07
C  MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
C  NV=(-0.00213)*( .5*RHO*L3*S)
C  NR=(-0.00105)*( .5*RHO*L4*S)
C  ND=(-0.0007)*( .5*RHO*L3*S**2)
C  NVVR=(-0.015)*( .5*RHO*L4/S)
C  NVRR=(-0.008)*( .5*RHO*L5/S)
C  NVVV=(0.01)*( .5*RHO*L3/S)
C  NRRR=(-0.006)*( .5*RHO*L6/S)
C  NDDD=(0.0001)*( .5*RHO*L3*S**2)
C  NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE,SPEED,ENCOUNTER FREQUENCY
C
C  NRDOT=(-0.00027)*( .5*RHO*L5)

```



```

C  SPEED=23 KNOTS,ENCOUNTER ANGLE=60,ENCOUNTER FREQ=0.75
C      NRDOT=-.26251D+12
C      NR=-.53637D+09
C      NRDOT=-.20125D+12
C      NR=-.94970D+10
C      NRDOT=-.18671D+12
C      NR=-.46860D+11
C      NRDOT=-.14518D+12
C      NR=-.87538D+11
C      NRDOT=-.37261D+11
C      NR=-.69856D+11
C  REGULAR WAVE SEA STATE
C      FX=WA*RX*DCOS(WE*TIME+TX)
C      FY=WA*RY*DCOS(WE*TIME+TY)
C      MZ=WA*RZ*DCOS(WE*TIME+TZ)
C  U ACTUAL SPEED
C  UC COMMANDED SPEED
C  XP = PROPELLER THRUST
C      XP=-XUU*UC**2
C  EQUATIONS OF MOTION
C      UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C      1 + XDD*D*D + FX + XP )/(MASS-XUDOT)
C      VDOT=(YV*V + (YR-MASS*U)*R + YD*D + YVVR*V**2*R
C      1 + YVRR*V*R**2 + YVVV*V**3
C      2 + YRRR*R**3 + YDDD*D**3 + FY )/(MASS-YVDOT)
C      RDOT=(NV*V + NR*R + ND*D + NVVR*V**2*R + NVRR*V*R**2
C      1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3 + MZ)/(IZ-NRDOT)
C  WHEN TO PRINTOUT
C      IF (ICOUNT.EQ.11) GO TO 50
C      GO TO 300
C  CONVERT RADIANS TO DEGREES
C      50  YAWDEG= YAW*57.296
C          RDEG=R*57.296
C          RDDEG=RDOT*57.296
C          DDEG=D*57.296

```

```

        YAWC=YAWC*57.296
        ICOUNT=1
C   TEST IF WANT TO STOP
    300  IF (TIME.GE.ETIME) GO TO 400
C   INTEGRATION STEP SIZE DELT
        DELT=1.0
C   INTEGRATION
        U=U+UDOT*DELT
        V=V+VDOT*DELT
        R=R+RDOT*DELT
        YAW=YAW+R*DELT
        X2=X2+DX2*DELT
C   CONVERT SHIP TO FIXED COORDINATES ON EARTH
C       XDOT=U*DCOS(YAW)-V*DSIN(YAW)
C       YDOT=U*DSIN(YAW)+V*DCOS(YAW)
C       X=X+XDOT*DELT
C       Y=Y+YDOT*DELT
        TIME=TIME+DELT
        ICOUNT=ICOUNT+1
        ISE=ISE + LAMDA*YAWC**2
        ISR=ISR + D**2
        GO TO 200
C   J=TDIFF= COST FUNCTION
    400  TDIFF=ISE+ISR
        WRITE(6,500) ISE,ISR,TDIFF,K1,T1,T2
    500  FORMAT(' ',1X,'ISE=',F15.7,' ISR=',F15.7,' TOTAL=',
        1F15.7,2X,'K1=',F15.7,2X,'T1=',F15.7,2X,'T2=',F15.7)
        RETURN
        END

```

The function minimization subroutine BOXPLX follows.  
Then the following two cards must be placed.

```

//GO.SYSIN DD *
/*

```

APPENDIX C  
SYSTEM'S RESPONSE FOR REGULAR SEAS

```
//REGURESP JOB (XXXX,XXXX), 'RESEARCH', CLASS=A
//*MAIN ORG=NPGVM1.XXXXP
// EXEC FORTXCG, PARM.FORT='OPT(2)', IMSL=DP, REGION=1024K
//FORT.SYSIN DD *
C  IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
C  OBTAINED CHANGE XS(*) TO X(*) AND DELETE XU(*), AND XL(*)
      COMMON J
      DIMENSION X(3)
      X(1)=1.5420017
      X(2)=141.2350922
      X(3)=23.8943634
C  CALL PLANT(X)
C  IF ONLY SIMULATION IS WANTED
      CALL PLANT(X)
      WRITE (6,25)
25  FORMAT(1X, ' OPTIMAL GAINS' ,/)
      DO 30 I=1,3
30  WRITE(6,40)I,X(I)
40  FORMAT(1X, 'X(' ,I2, ' )=' ,F14.7)
      WRITE(6,50) J
50  FORMAT(1X, 'J = ' ,E15.10)
      STOP
      END
      SUBROUTINE PLANT(XX)
C  SUBROUTINE PLANT(XX) SIMULATES THE SHIP
      COMMON TDIFF
      REAL*8 L,L2,L3,L4,L5,L6
      REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
      REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
      REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT
```

```

      REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
      REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT,MZI,WA,WE
      REAL*8 DYAW,YAW,YAWC,ISE,ISR,LAMDA,D,RYR,RYI,MZR
      REAL*8 K1,T1,T2,D,X2,DX2,S,RX,RY,RZ,TX,TY,TZ,RXR,RXI
      DIMENSION XX(3)

C
C  CLOSE LOOP ANALYSIS WITH FILTER
C
C  INITIAL CONDITIONS FOR INTEGRATION
C  SIMULATION END TIME IN SECONDS
      ETIME=600.
      TIME=0.0
      ICOUNT=1
C  INITIALIZE THE COST FUNCTION
      ISE=0.0
      ISR=0.0
      TDIFF=0.0
      LAMDA=8.128
C  GAIN COEFFICIENTS TO BE OPTIMIZED
      K1=XX(1)
      T1=XX(2)
      T2=XX(3)
C      WRITE(6,1010) K1,T1,T2
C1010  FORMAT(1X,'K1 =',F15.7,' T1 =',F15.7,' T2 =',F15.7)
C  X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
      X=0.0
      Y=0.0
      XDOT=0.0
      YDOT=0.0
C  U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
      V=0.0
      UDOT=0.0
      VDOT=0.0
      YAW=0.0
      R=0.0

```

```

        RDOT=0.0
C   ORDERED SPEED IN FEET/SEC
C   38.82 FT/SEC=23 KNOTS
        UC=38.82
C   AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
        U=UC
C   D = RUDDER ANGLE
        D=0.0
        L=880.5
        L2=L**2
        L3=L*L*L
        L4=L*L3
        L5=L*L4
        L6=L*L5
C   SEA DISTURBANCE
C   FORCES IN X,Y DIRECTION COMPUTED IN FORCES
C   MOMENTS IN Z
        FX=0.
        FY=0.
        MZ=0.
        RXR=-.91037D+03
        RXI=0.50896D+05
        RYR=-.20256D+04
        RYI=.18077D+06
        MZR=-.14310D+08
        MZI=-.16903D+07
        RX=DSQRT(RXR**2+RXI**2)
        RY=DSQRT(RYR**2+RYI**2)
        RZ=DSQRT(MZR**2+MZI**2)
        TX=DATAN2(RXI,RXR)
        TY=DATAN2(RYI,RYR)
        TZ=DATAN2(MZI,MZR)
C   SIGNIFICANT WAVE HEIGHT; SEA STATE 1-0.32,2-0.75,3-2.5,
C   4-5.0,5-7.5,6-10.0,7-17.5,8-20.5,9-27.0
        WA=27.0

```

```

C   ENCOUNTER FREQUENCY .1,.2,.3,.4,.5,.6,.75,1.0,1.5,2.5
      WE=0.2
C   HYDRODYNAMIC COEFFICIENTS ARE INSERTED AS PARAMETERS
      RHO=1.9876
      MASS=(.0044)*(.5*RHO*L3)
      IZ=(0.00028)*(.5*RHO*L5)
      YAWC=0.0
      X2=0.0
      DX2=0.0
200  CONTINUE
      S=DSQRT(U**2+V**2)
C   INPUT YAW COMMAND
      YAWC=0.0
      IF (TIME.GE.0.0) YAWC=0.0
C   ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL - YAW ORDERED)
C   ( COMPENSATOR FILTER )
      YAWC=YAW - YAWC
      DX2=(YAWC-X2)/T2
      D=K1*(T1*DX2+X2)
C   AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C   XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C   DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER FREQUENCY
C
      XUDOT=(-.0001)*(.5*RHO*L3)
      XU=(-0.0253)*(.5*RHO*L2*S)
      XUU=(-0.0003)*(.5*RHO*L2)
      XVR=(0.0039)*(.5*RHO*L3)
      XVV=(-.0012)*(.5*RHO*L2)
      XDD=(-0.0005)*(.5*RHO*L2*S**2)
C   LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
C
      YV=(-0.00758)*(.5*RHO*L2*S)
      YR=(0.0023)*(.5*RHO*L3*S)
      YD=(0.00145)*(.5*RHO*L2*S**2)
      YVVR=(0.01)*(.5*RHO*L3/S)
      YVRR=(-0.008)*(.5*RHO*L4/S)

```



```

YVVV=(-0.03)*(.5*RHO*L2/S)
YRRR=(0.003)*(.5*RHO*L5/S)
YDDD=(-0.0005)*(.5*RHO*L2*S**2)
C  YUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C  DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER FREQUENCY
C
C  YVDOT=(-0.0039)*(.5*RHO*L3)
C  SPEED=23 KNOTS,ENCOUNTER ANGLE=60,ENCOUNTER FREQ=0.75
YVDOT=-.30908+07
YV=-0.81271D+04
C  MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
NV=(-0.00213)*(.5*RHO*L3*S)
C  NR=(-0.00105)*(.5*RHO*L4*S)
ND=(-0.0007)*(.5*RHO*L3*S**2)
NVVR=(-0.015)*(.5*RHO*L4/S)
NVRR=(-0.008)*(.5*RHO*L5/S)
NVVV=(0.01)*(.5*RHO*L3/S)
NRRR=(-0.006)*(.5*RHO*L6/S)
NDDD=(0.0001)*(.5*RHO*L3*S**2)
C  NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE,SPEED,ENCOUNTER FREQUENCY
C
C  NRDOT=(-0.00027)*(.5*RHO*L5)
C  SPEED=32 KNOTS,ENCOUNTER ANGLE=60,ENCOUNTER FREQ=0.75
NRDOT=-0.26251D+12
NR=-0.53637D+09
C  REGULAR WAVE SEA STATE
FX=WA*RX*DCOS(WE*TIME+TX)
FY=WA*RY*DCOS(WE*TIME+TY)
MZ=WA*RZ*DCOS(WE*TIME+TZ)
C  U ACTUAL SPEED
C  UC COMMANDED SPEED
C  XP = PROPELLER THRUST
XP=-XUU*UC**2
C  EQUATIONS OF MOTION

```

```

C      UDOT=( (XVR + MASS)*V*R + XU*U**2 + XV*V**2
C      1 + XDD*D*D + FX + XP )/(MASS-XUDOT)
      VDOT=(YV*V + (YR-MASS*U)*R + YD*D + YVVR*V**2*R
      1 + YVRR*V*R**2 + YVVV*V**3
      2 + YRRR*R**3 + YDDD*D**3 + FY )/(MASS-YVDOT)
      RDOT=(NV*V + NR*R + ND*D + NVVR*V**2*R + NVRR*V*R**2
      1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3 + MZ)/(IZ-NRDOT)
C  WHEN TO PRINTOUT
      IF (ICOUNT.EQ. 2) GO TO 50
      GO TO 300
C  CONVERT RADIANS TO DEGREES
50  YAWDEG= YAW*57.296
      RDEG=R*57.296
      RDDEG=RDOT*57.296
      DDEG=D*57.296
      YAWC=YAWC*57.296
      WRITE (6,101) TIME,YAWDEG
101  FORMAT(1X,F12.8,1X,F12.8)
      ICOUNT=1
C  TEST IF WANT TO STOP
300  IF (TIME.GE.ETIME) GO TO 400
C  INTEGRATION STEP SIZE DELT
      DELT=1.0
C  INTEGRATION
      U=U+UDOT*DELT
      V=V+VDOT*DELT
      R=R+RDOT*DELT
      YAW=YAW+R*DELT
      X2=X2+DX2*DELT
C  CONVERT SHIP TO FIXED COORDINATES ON EARTH
C      XDOT=U*DCOS(YAW)-V*DSIN(YAW)
C      YDOT=U*DSIN(YAW)+V*DCOS(YAW)
C      X=X+XDOT*DELT
C      Y=Y+YDOT*DELT
      TIME=TIME+DELT

```

```

        ICOUNT=ICOUNT+1
        ISE=ISE + LAMDA*YAWE**2
        ISR=ISR + D**2
        GO TO 200
C  J=TDIFF= COST FUNCTION
400  TDIFF=ISE+ISR
        WRITE(6,500) ISE,ISR,TDIFF,K1,T1,T2
500  FORMAT(' ',1X,'ISE=',F15.7,'   ISR=',F15.7,'   TOTAL=',
1  F15.7,2X,'K1=',F15.7,2X,'T1=',F15.7,2X,'T2=',F15.7)
        RETURN
        END
//GO.SYSIN DD *
/*

```

APPENDIX D  
IRREGULAR SEASTATE FORMULATION

```
//IRREGAINS JOB (XXXX,XXXX), 'RESEARCH', CLASS=C
//*MAIN ORG=NPGVM1.XXXXP
// EXEC FORTXCG, PARM.FORT='OPT.(2)', IMSL=DP, REGION=1024K
//FORT.SYSIN DD *
C  IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
C  OBTAINED CHANGE XS(*) TO X(*) AND DELETE XU(*), AND XL(*)
      DIMENSION XS(3), XU(3), XL(3)
      XS(1)=0.655751
      XS(2)=90.5483
      XS(3)=36.74847
C  XS(I) IS THE STARTING GUESS
C  XL(I) IS THE LOWER LIMIT FOR THE I'TH VARIABLE
C  XU(I) IS THE UPPER LIMIT FOR THE I'TH VARIABLE
      XL(1)=0.01
      XU(1)=2.0
      XL(2)=20.0
      XU(2)=180.0
      XL(3)=5.0
      XU(3)=180.0
C  A DESCRIPTION OF THE FOLLOWING PARAMETERS
C  IS DISCUSSED IN BOXPLX
      R=9./13.
      NTA=1000
      NPR=100
      NAV=0
      NV=3
      IP=0
C  THE FOLLOWING STATEMENT MUST BE CHANGED TO
C  CALL PLANT(X)
C  IF ONLY SIMULATION IS WANTED
```

```

        CALL BOXPLX(NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)
        WRITE (6,25)
25      FORMAT(1X,' OPTIMAL GAINS',/)
        DO 30 I=1,3
30      WRITE(6,40)I,XS(I)
40      FORMAT(1X,'X(',I2,')=' ,F14.7)
        STOP
        END
        SUBROUTINE PLANT(XX)
C  SUBROUTINE PLANT(XX) SIMULATES THE SHIP
        COMMON TDIFF
        REAL*8 L,L2,L3,L4,L5,L6
        REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
        REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
        REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT
        REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
        REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT
        REAL*8 DYAW,YAW,YAWC,ISE,ISR,LAMDA,D
        REAL*8 K1,T1,T2,T3,T4,D,X2,DX2,X3,DX3,X4,CH(11),S
        DIMENSION XX(3)
C
C  CLOSE LOOP ANALYSIS WITH FILTER
C
C  INITIAL CONDITIONS FOR INTEGRATION
C  SIMULATION END TIME IN SECONDS
        ETIME=600.
        TIME=0.0
        ICOUNT=1
C  INITIALIZE THE COST FUNCTION
        ISE=0.0
        ISR=0.0
        TDIFF=0.0
        LAMDA=8.128
C  GAIN COEFFICIENTS TO BE OPTIMIZED
        K1=XX(1)

```

```

      T1=XX(2)
      T2=XX(3)
C      WRITE(6,1010) K1,T1,T2
C      X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
      X=0.0
      Y=0.0
      XDOT=0.0
      YDOT=0.0
C      U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
      V=0.0
      UDOT=0.0
      VDOT=0.0
      YAW=0.0
      R=0.0
      RDOT=0.0
C      ORDERED SPEED IN FEET/SEC
C      38.82 FT/SEC=23 KNOTS
      UC=38.82
C      AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
      U=UC
C      D = RUDDER ANGLE
      D=0.0
      L=880.5
      L2=L**2
      L3=L*L*L
      L4=L*L3
      L5=L*L4
      L6=L*L5
C      SEA DISTURBANCE
C      FORCES IN X,Y DIRECTION COMPUTED IN FORCES
C      MOMENTS IN Z
      FX=0.
      FY=0.
      MZ=0.
C      ISEA IS A SWITCH ;ISEA=0 (CALM WATER) ISEA=1 (SEA STATE)

```



```

ISEA=1
C  HYDRODYNAMIC COEFFICIENTS ARE INSERTED AS PARAMETERS
    RHO=1.9876
    MASS=(.0044)*(.5*RHO*L3)
    IZ=(0.00028)*(.5*RHO*L5)
    YAW=0.0
    X2=0.0
    DX2=0.0
200 CONTINUE
    S=DSQRT(U**2+V**2)
C  INPUT YAW COMMAND
    YAWC=0.0
    IF (TIME.GE.0.0) YAWC=0.0
C  ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL - YAW ORDERED)
C  ( CONTROLLER FILTER )
    YAWE=YAW - YAWC
    DX2=(YAWE-X2)/T2
    D=K1*(T1*DX2+X2)
C  AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C  XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C  DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER FREQUENCY
C
    XUDOT=(-.0001)*(.5*RHO*L3)
    XU=(-0.0253)*(.5*RHO*L2*S)
    XUU=(-0.0003)*(.5*RHO*L2)
    XVR=(0.0039)*(.5*RHO*L3)
    XVV=(-.0012)*(.5*RHO*L2)
    XDD=(-0.0005)*(.5*RHO*L2*S**2)
C  LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
    YV=(-0.00758)*(.5*RHO*L2*S)
    YR=(0.0023)*(.5*RHO*L3*S)
    YD=(0.00145)*(.5*RHO*L2*S**2)
    YVVR=(0.01)*(.5*RHO*L3/S)
    YVRR=(-0.008)*(.5*RHO*L4/S)
    YVVV=(-0.03)*(.5*RHO*L2/S)

```

```

      YRRR=(0.003)*(.5*RHO*L5/S)
      YDDD=(-0.0005)*(.5*RHO*L2*S**2)
C   YUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C   DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER FREQUENCY
C
C      YVDOT=(-0.0039)*(.5*RHO*L3)
C   SPEED=23 KNOTS, ENCOUNTER FREQUENCY =0.75
      YVDOT=-2304300.0
C   MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
      NV=(-0.00213)*(.5*RHO*L3*S)
      NR=(-0.00105)*(.5*RHO*L4*S)
      ND=(-0.0007)*(.5*RHO*L3*S**2)
      NVVR=(-0.015)*(.5*RHO*L4/S)
      NVRR=(-0.008)*(.5*RHO*L5/S)
      NVVV=(0.01)*(.5*RHO*L3/S)
      NRRR=(-0.006)*(.5*RHO*L6/S)
      NDDD=(0.0001)*(.5*RHO*L3*S**2)
C   NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C   FOR DIFFERENT ENCOUNTER ANGLE,SPEED,ENCOUNTER FREQUENCY
C
C      NRDOT=(-0.00027)*(.5*RHO*L5)
C   SPEED=23 KNOTS, ENCOUNTER FREQUENCY =0.75
      NRDOT=-1.4518E+11
C   SETS SEA STATE TO ZERO
      IF (ISEA.EQ.1) GO TO 30
      FX=0.
      FY=0.
      MZ=0.
      GO TO 35
C   UNIT 12 HAS THE SEA STATE DATA NAMED CH
C   IT MUST BE SYNCHRONIZED BY TIME
30   READ (12) CH
      FX=CH(3)
      FY=CH(4)
      MZ=CH(8)

```

```

35    CONTINUE
C    U ACTUAL SPEED
C    UC COMMANDED SPEED
C    XP = PROPELLER THRUST
      XP=-XUU*UC**2
C    EQUATIONS OF MOTION
C      UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C    1 + XDD*D*D + FX + XP )/(MASS-XUDOT)
      VDOT=(YV*V + (YR-MASS*U)*R + YD*D + YVVR*V**2*R
C    1 + YVRR*V*R**2 + YVVV*V**3
C    2 + YRRR*R**3 + YDDD*D**3 + FY )/(MASS-YVDOT)
      RDOT=(NV*V + NR*R + ND*D + NVVR*V**2*R + NVRR*V*R**2
C    1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3 + MZ)/(IZ-NRDOT)
C    WHEN TO PRINTOUT
      IF (ICOUNT.EQ.11) GO TO 50
      GO TO 300
C    CONVERT RADIANS TO DEGREES
50    YAWDEG= YAW*57.296
      RDEG=R*57.296
      RDDEG=RDOT*57.296
      DDEG=D*57.296
      YAWC=YAWC*57.296
      ICOUNT=1
C    TEST IF WANT TO STOP
300   IF (TIME.GE.ETIME) GO TO 400
C    INTEGRATION STEP SIZE DELT
      DELT=1.0
C    INTEGRATION
      U=U+UDOT*DELT
      V=V+VDOT*DELT
      R=R+RDOT*DELT
      YAW=YAW+R*DELT
      X2=X2+DX2*DELT
C    CONVERT SHIP TO FIXED COORDINATES ON EARTH
C      XDOT=U*DCOS(YAW)-V*DSIN(YAW)

```

```

C      YDOT=U*DSIN(YAW)+V*DCOS(YAW)
C      X=X+XDOT*DELT
C      Y=Y+YDOT*DELT
      TIME=TIME+DELT
      ICOUNT=ICOUNT+1
      ISE=ISE + LAMDA*YAW**2
      ISR=ISR + D**2
      GO TO 200
C  J=TDIFF= COST FUNCTION
400   TDIFF=ISE+ISR
      WRITE(6,500) TDIFF,K1,T1,T2
500   FORMAT(' ',1X,'TOTAL =',F15.7,' K1 =',F15.7,
1    ' T1 =',F15.7,2X,'T2=',F15.7)
      REWIND 12
      RETURN
      END

```

The function minimization subroutine BOXPLX follows.  
Then the following three cards must be placed.

```

//GO.SYSIN DD *
/*
/ GO.FT12F001 DD DISP=SHR,DSN=MSS.S2160.A241

```

APPENDIX E  
SYSTEM'S RESPONSE FOR IRREGULAR SEAS

```
//IRRERESP JOB (XXXX,XXXX), 'RESEARCH', CLASS=B
//*MAIN ORG=NPGVML.XXXXP
// EXEC FRTXCLGP,IMSL=DP,REGION=1024K
//FORT.SYSIN DD *
C  IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
C  OBTAINED
      DIMENSION XX(3)
C  OPTIMAL GAINS FOR CONTROLLER
      XX(1)=.9192610
      XX(2)=18.5788116
      XX(3)=9.77668
C  THE SUBROUTINE PLANT SIMULATES THE SL-7 CONTAINERSHIP
      CALL PLANT(XX)
      WRITE(6,25)
25  FORMAT(1X, 'OPTIMAL GAINS',/)
      DO 30 I=1,3
30  WRITE(6,40)I,XX(I)
40  FORMAT(1X, 'XX(', I2, ')=' , F14.7)
      STOP
      END
C
C  SUBROUTINE PLANT(XX)  SIMULATES THE SHIP
      SUBROUTINE PLANT(XX)
      COMMON TDIFF
      REAL*8 L,L2,L3,L4,L5,L6
      REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
      REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
      REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT
      REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
      REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT
```

```

      REAL*8 DYAW, YAW, YAWC, ISE, ISR, LAMDA, D
      REAL*8 K1, T1, T2, D, X2, DX2, S, CH(11), DX3, X3, X4
      DIMENSION XX(3)

C
C  CLOSE LOOP ANALYSIS WITH FILTER
C
      INITIAL CONDITIONS FOR INTEGRATION
C  SIMULATION END TIME IN SECONDS
      ETIME=600.
      TIME=0.0
      ICOUNT=1
C  INITIALIZE THE COST FUNCTION
      ISE=0.0
      ISR=0.0
      TDIFF=0.0
      LAMDA=4.2
C  GAIN COEFFICIENTS
      K1=XX(1)
      T1=XX(2)
      T2=XX(3)
C  X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
      X=0.0
      Y=0.0
      XDOT=0.0
      YDOT=0.0
C  U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
      V=0.0
      UDOT=0.0
      VDOT=0.0
      YAW=0.0
      R=0.0
      RDOT=0.0
      YAW=0.0
C  ORDERED SPEED IN FEET/SEC
C  38.81 FT/SEC=23 KNOTS

```



```

      UC=38.81
C   AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
      U=UC
C   D = RUDDER ANGLE
      D=0.0
      L=880.5
      L2=L**2
      L3=L*L*L
      L4=L*L3
      L5=L*L4
      L6=L*L5
C   SEA DISTURBANCE
C   FORCES IN X,Y DIRECTION.COMPUTED IN FORCES
C   MOMENTS IN Z
      FX=0.
      FY=0.
      MZ=0.
C   ISEA IS A SWITCH; ISEA=0 (CALM WATER) ISEA=1 (SEA STATE)
      ISEA=1
C   HYDRODYNAMIC COEFFICIENTS ARE INSERTED AS PARAMETERS
      RHO=1.9876
      MASS=(.0044)*(.5*RHO*L3)
      IZ=(0.00028)*(.5*RHO*L5)
      YAWE=0.0
      X2=0.0
      DX2=0.0
      X3=0.0
      DX3=0.0
      X4=0.0
200 CONTINUE
      S=DSQRT(U**2 + V**2)
C   INPUT YAW COMMAND
      YAWC=0.0
      IF (TIME.GE.0.0) YAWC=0.0
C   ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL - YAW ORDERED)

```

```

C  ( COMPENSATOR FILTER )
    YAWE=YAW - YAWC
    DX2=(YAWE-X2)/T2
    X4=K1*(T1*DX2+X2)
    DX3=(X4-X3)/T4
    D=(T3*DX3+X3)
C  AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C
C  XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C  DIFFERENT ENCOUNTER ANGLE AND SPEED.
C    XUDOT=(-.0001)*(.5*RHO*L3)
    XUW=(-0.0003)*(.5*RHO*L2)
    XVR=(0.0039)*(.5*RHO*L3)
    XVV=(-.0012)*(.5*RHO*L2)
    XDD=(-0.0005)*(.5*RHO*L2*S**2)
C  LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
    YV=(-0.00758)*(.5*RHO*L2*S)
    YR=(0.0023)*(.5*RHO*L3*S)
    YD=(0.00145)*(.5*RHO*L2*S**2)
    YVVR=(0.01)*(.5*RHO*L3/S)
    YVRR=(-0.008)*(.5*RHO*L4/S)
    YVVV=(-0.03)*(.5*RHO*L2/S)
    YRRR=(0.003)*(.5*RHO*L5/S)
    YDDD=(-0.0005)*(.5*RHO*L2*S**2)
C  YUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C  DIFFERENT ENCOUNTER ANGLE AND SPEED.
C
C    YVDOT=(-0.0039)*(.5*RHO*L3)
    YVDOT=-3654800.00
C  MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
    NV=(-0.00213)*(.5*RHO*L3*S)
    NR=(-0.00105)*(.5*RHO*L4*S)
    ND=(-0.0007)*(.5*RHO*L3*S**2)
    NVVR=(-0.015)*(.5*RHO*L4/S)
    NVRR=(-0.008)*(.5*RHO*L5/S)

```

```

      NVVV=(0.01)*(.5*RHO*L3/S)
      NRRR=(-0.006)*(.5*RHO*L6/S)
      NDDD=(0.0001)*(.5*RHO*L3*S**2)
C   NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C   FOR DIFFERENT ENCOUNTER ANGLE AND SPEED.
C
C      NRDOT=(-0.00027)*(.5*RHO*L5)
      NRDOT=-2.1815E+11
C   SETS SEA STATE TO ZERO
      IF (ISEA.EQ.1) GO TO 30
      FX=0.
      FY=0.
      MZ=0.
      GO TO 35
C   UNIT 12 HAS THE SEA STATE DATA NAMED CH
C   IT MUST BE SYNCHRONIZED BY TIME
30      READ (12) CH
      FX= CH(3)
      FY= CH(4)
      MZ= CH(8)
35      CONTINUE
C   U ACTUAL SPEED
C   UC COMMANDED SPEED
C   XP = PROPELLER THRUST
      XP=-XUU*UC**2
C   EQUATIONS OF MOTION
C      UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C      1 + XDD*D*D + FX + XP )/(MASS-XUDOT)
      VDOT=(YV*V + (YR-MASS*S)*R + YD*D + YVVR*V**2*R
      1 + YVRR*V*R**2 + YVVV*V**3
      1 + YRRR*R**3 + YDDD*D**3 + FY )/(MASS-YVDOT)
      RDOT=(NV*V + NR*R + ND*D + NVVR*V**2*R + NVRR*V*R**2
      1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3 + MZ)/(IZ-NRDOT)
C   WHEN TO PRINTOUT
      IF (ICOUNT.EQ.2 ) GO TO 50

```

```

      GO TO 300
C   CONVERT RADIANS TO DEGREES
50   YAWDEG= YAW*57.296
      RDEG=R*57.296
      RDDEG=RDOT*57.296
      DDEG=D*57.296
      YAWC=YAWC*57.296
      WRITE (6,100) TIME,YAWDEG
100  FORMAT(1X,F12.8,1X,F12.8)
      ICOUNT=1
C   TEST IF WANT TO STOP
300  IF (TIME.GE.ETIME) GO TO 400
C   INTEGRATION STEP SIZE DELT
      DELT=1.
C   INTEGRATION
      U=U+UDOT*DELT
      V=V+VDOT*DELT
      R=R+RDOT*DELT
      YAW=YAW+R*DELT
      X2=X2+DX2*DELT
      X3=X3+DX3*DELT
C   CONVERT SHIP TO FIXED COORDINATES ON EARTH
      XDOT=U*DCOS(YAW)-V*DSIN(YAW)
      YDOT=U*DSIN(YAW)+V*DCOS(YAW)
      X=X+XDOT*DELT
      Y=Y+YDOT*DELT
      TIME=TIME+DELT
      ICOUNT=ICOUNT+1
      ISE=ISE + LAMDA*YAWC**2
      ISR=ISR + D**2
      GO TO 200
C   J=TDIFF= COST FUNCTION
400  TDIFF=ISE+ISR
      WRITE(6,500) ISE,ISR,TDIFF
500  FORMAT('1',5X,'ISE=',F15.7,'   ISR=',F15.7,

```

1 ' TOTAL=' ,F15.7)

STOP

END

//GO.SYSIN DD \*

/\*

//GO.FT12F001 DD DISP=SHR,DSN=MSS.S2160.A211

APPENDIX F  
MODIFIED MINIMIZATION SUBROUTINE

```
SUBROUTINE BOXPLX (NV,NAV,NPR,NTZ,RZ,XS,IP,BU,BL,YMN,IER)
C
DIMENSION V(50,50), FUN(50), SUM(25), CEN(25), XS(NV),
      1BU(NV),BL(NV)
C
      KV = 5
      EP = 1.E-4
      NTA = 2000
      IF (NTZ.GT.0) NTA = NTZ
      R = RZ
      IF (R.LE.0..OR.R.GE.1.) R=1./3.
      NVT = NV+NAV
C
C      TOTAL VARS, EXPLICIT PLUS IMPLICIT
      NT = 0
C      CURRENT TRIAL NO.
      NPT = 0
C      CURRENT NO. OF PERMISSIBLE TRIALS
      NTFS = 0
C      CURRENT NO. OF TIMES F HAS BEEN ALMOST UNCHANGED
C
C      CHECK FEASIBILITY OF START POINT
C
      DO 4 I=1,NV
      VT = XS(I)
      IF (BL(I).LE.VT) GO TO 1
      II = -I
      VT = BL(I)
      GO TO 2
1 IF (BU(I).GE.VT) GO TO 3
```



```

      II = I
      VT = BU(I)
2  IF (NPR.GT.0) WRITE (6,49) II
3  V(I,1) = VT
      CEN(I) = VT
      IF (IP.EQ.1) GO TO 4
      BL(I) = BL(I)+AMAX1(EP,EP*ABS(BL(I)))
      BU(I) = BU(I)-AMAX1(EP,EP*ABS(BU(I)))
4  SUM(I) = VT
C
C
      NCE = 1
C  NUMBER OF CONSTRAINT EVALUATIONS
      I = 1
      IF (KE(V(1,1)).EQ.0) GO TO 5
      IF (NPR.LE.0) GO TO 12
      WRITE (6,50)
      GO TO 12
5  NFE = 1
C
C  NUMBER OF VERTICES (K) = 2 TIMES NO. OF VARIABLES.
      K = (2*NV)/3
C
C  NUMBER OF DISPLACEMENTS ALLOWED.
      NLIM = 5*NV+10
C
C  NUMBER OF CONSECUTIVE TRIALS WITH UNCHANGED FE TO
C  TO TERMINATE
      NCT = NLIM+NV
      ALPHA = 1.3
      FK = K
      FKM = FK-1.
      BETA = ALPHA+1.
C
C  INSURE SEED OF RANDOM NUMBER GENERATOR IS ODD.

```

```

      IQR = R*1.E7
      IF (MOD(IQR,2).EQ.0) IQR=IQR+101
C
C   SET UP INITIAL VERTICES
      FUN(1) = FE(V(1,1))
      YMN = FUN(1)
6   FI = 1.
      FUNOLD = FUN(1)
C
      DO 15 I=2,K
      FI = FI+1.
      LIMT = 0
7   LIMT = LIMT+1
C
C   END CALCULATION IF FEASIBLE CENTROID CANNOT BE FOUND.
      IF (LIMT.GE.NLIM) GO TO 11
C
      DO 8 J=1,NV
C
C   RANDOM NUMBER GENERATOR (RANDU)
      IQR = IQR*65539
      IF (IQR.LT.0) IQR = IQR+2147483647+1
      RQX = IQR
      RQX = RQX*.4656613E-9
      V(J,I) = BL(J)+RQX*(BU(J)-BL(J))
      IF (IP.EQ.1) V(J,I)=AINT(V(J,I)+.5)
8   CONTINUE
C
      DO 10 L=1,NLIM
      NCE = NCE+1
      IF (KE(V(1,I)).EQ.0) GO TO 13
C
      DO 9 J=1,NV
      VT = .5*(V(J,I)+CEN(J))
      IF (IP.EQ.1) VT = AINT(VT+.5)

```

```

        V(J,I) = VT
    9  CONTINUE
C
    10 CONTINUE
C
    11 IF (NPR.LE.0) GO TO 12
        WRITE (6,51) I
        CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,I,FUN,CEN,I)
    12 IER = -1
        GO TO 48
C
    13 DO 14 J=1,NV
        SUM(J) = SUM(J)+V(J,I)
    14 CEN(J) = SUM(J)/FI
C
C  TRY TO ASSURE FEASIBLE CENTROID FOR STARTING.
        NCE = NCE+1
        IF (KE(CEN).EQ.0) GO TO 60
        SUM(J) = SUM(J) -V(J,I)
        GO TO 7
    60 NFE = NFE+1
        FUN(I) = FE(V(1,I))
    15 CONTINUE
C
C  END OF LOOP SETTING OF INITIAL COMPLEX.
        IF (NPR.LE.0) GO TO 17
        CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,0)
C
C  FIND THE WORST VERTEX, THE 'J'TH.
        J = 1
C
        DO 16 I=2,K
            IF (FUN(J).GE.FUN(I)) GO TO 16
            J = I
    16 CONTINUE

```

```

C
C  BASIC LOOP.  ELIMINATE EACH WORST VERTEX IN TURN.
C  IT MUST BECOME NO LONGER WORST, NOT MERELY IMPROVED.
C  FIND NEXT-TO-WORST VERTEX,  THE 'JN'TH ONE.
17 JN = 1
   IF (J.EQ.1) JN = 2
C
   DO 18 I=1,K
   IF (I.EQ.J) GO TO 18
   IF (FUN(JN).GE.FUN(I)) GO TO 18
   JN = I
18 CONTINUE
C
C  LIMIT = NUMBER OF MOVES DURING THIS TRIAL TOWARD THE
C  CENTROID DUE TO FUNCTION VALUE.
   LIMIT = 1
C
C  COMPUTE CENTROID AND OVER REFLECT WORST VERTEX.
C
   DO 19 I=1,NV
   VT = V(I,J)
   SUM(I) = SUM(I)-VT
   CEN(I) = SUM(I)/FKM
   VT = BETA*CEN(I)-ALPHA*VT
   IF (IP.EQ.1) VT = AINT(VT+.5)
C
C  INSURE THE EXPLICIT CONSTRAINTS ARE OBSERVED.
19 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C
   NT = NT+1
C
C  CHECK FOR IMPLICIT CONSTRAINT VIOLATION.
C
20 DO 25 N=1,NLIM
   NCE = NCE+1

```

```

        IF (KE(V(1,J)).EQ.0) GO TO 26
C
C   EVERY 'KV'TH TIME, OVER-REFLECT THE OFFENDING VERTEX
C   THROUGH THE BEST VERTEX.
        IF (MOD(N,KV).NE.0) GO TO 22
        CALL FBV (K,FUN,M)
C
        DO 21 I=1,NV
        VT = BETA*V(I,M)-ALPHA*V(I,J)
        IF (IP.EQ.1) VT = AINT(VT+.5)
21  V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C
        GO TO 24
C
C   CONSTRAINT VIOLATION:  MOVE NEW POINT TOWARD CENTROID.
C
22  DO 23 I=1,NV
        VT = .5*(CEN(I)+V(I,J))
        IF (IP.EQ.1) VT = AINT(VT+.5)
        V(I,J) = VT
23  CONTINUE
C
24  NT = NT+1
25  CONTINUE
C
        IER = 1
C
C   CANNOT GET FEASIBLE VERTEX BY MOVING TOWARD CENTROID,
C   OR BY OVER-REFLECTING THRU THE BEST VERTEX.
        IF (NPR.LE.0) GO TO 42
        WRITE (6,52) NT,J
        CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,J)
        GO TO 42
C
C   FEASIBLE VERTEX FOUND, EVALUATE THE OBJECTIVE FUNCTION.

```

```

26 NFE = NFE+1
   FUNTRY = FE(V(1,J))
C
C TEST TO-SEE IF FUNCTION VALUE HAS NOT CHANGED.
   AFO = ABS(FUNTRY-FUNOLD)
   AMX = AMAX1(ABS(EP*FUNOLD),EP)
C
C ACTIVATE THE FOLLOWING TWO STATEMENTS
C FOR DIAGNOSTIC PURPOSES ONLY.
C   WRITE (6,99) J,AFO,AMX,FUNTRY,FUNOLD,FUN(J),FUN(JN),
C   INTFS,N
C 99 FORMAT (1X,I3,6E15.7,2I5)
   IF (AFO.GT.AMX) GO TO 27
   NTFS = NTFS+1
   IF (NTFS.LT.NCT) GO TO 28
   IER = 0
   IF (NPR.LE.0) GO TO 42
   WRITE (6,53) K
   CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,0)
   GO TO 42
27 NTFS = 0
C
C IS THE NEW VERTEX NO LONGER WORST?
28 IF (FUNTRY.LT.FUN(JN)) GO TO 34
C
C TRIAL VERTEX IS STILL WORST; ADJUST TOWARD CENTROID.
C EVERY 'KV'TH TIME, OVER-REFLECT THE OFFENDING VERTEX
C THROUGH THE BEST VERTEX.
   LIMT = LIMT+1
   IF (MOD(LIMT,KV).NE.0) GO TO 30
   CALL FBV (K,FUN,M)
C
DO 29 I=1,NV
VT = BETA*V(I,M)-ALPHA*V(I,J)
IF (IP.EQ.1) VT = AINT(VT+.5)

```



```

29 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C
      GO TO 32
C
30 DO 31 I=1,NV
      VT = .5*(CEN(I)+V(I,J))
      IF (IP.EQ.1) VT = AINT(VT+.5)
      V(I,J) = VT
31 CONTINUE
C
32 IF (LIMT.LT.NLIM) GO TO 33
C
C   CANNOT MAKE THE 'J'TH VERTEX NO LONGER WORST BY
C   DISPLACING TOWARD THE CENTROID OR BY OVER-REFLECTING
C   THRU THE BEST VERTEX.
      IER = 2
      IF (NPR .LE. 0) GO TO 42
      WRITE (6,52) NT, J
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,J)
      GO TO 42
33 NT = NT+1
      GO TO 20
C
C   SUCCESS: WE HAVE A REPLACEMENT FOR VERTEX J.
34 FUN(J) = FUNTRY
      FUNOLD = FUNTRY
      NPT = NPT+1
C
C   STOP AT THE 100'TH PERMISSIBLE TRIAL
      IF (MOD(NPT,100).EQ.0) GO TO 48
C
      DO 36 I=1,NV
      SUM(I) = 0.
C
      DO 35 N=1,K

```

```

35 SUM(I) = SUM(I)+V(I,N)
C
    CEN(I) = SUM(I)/FK
36 CONTINUE
C
    LC = 0
    GO TO 39
C
37 DO 38 I=1,NV
38 SUM(I) = SUM(I)+V(I,J)
C
    LC = J
C
39 IF (NPR.LE.0) GO TO 40
    IF (MOD(NPT,NPR).NE.0) GO TO 40
C
    CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,LC)
C
C HAS THE MAX. NUMBER OF TRIALS BEEN REACHED WITHOUT
C CONVERGENCE ? IF NOT, GO TO NEW TRIAL.
40 IF (NT.GE.NTA) GO TO 41
C
C NEXT-TO-WORST VERTEX NOW BECOMES WORST.
    J = JN
    GO TO 17
41 IER = 3
    IF (NPR.GT.0) WRITE (6,54)
C
C COLLECTOR POINT FOR ALL ENDINGS.
C 1) CANNOT DEVELOP FEASIBLE VERTEX. IER = 1
C 2) CANNOT DEVELOP A NO-LONGER-WORST VERTEX. IER = 2
C 3) FUNCTION VALUE UNCHANGED FOR K TRIALS. IER = 0
C 4) LIMIT ON TRIALS REACHED. IER = 3
C 5) CANNOT FIND FEASIBLE VERTEX AT START. IER = -1
42 CONTINUE

```

```

C
C  FIND BEST VERTEX.
      CALL FBV (K,FUN,M)
      IF (IER.GE.3) GO TO 44
C  RESTART IF THIS SOLUTION IS SIGNIFICANTLY BETTER THAN
C  THE PREVIOUS OR IF THIS IS THE FIRST TRY.
      IF (NPR.LE.0) GO TO 43
      WRITE (6,55) (M,YMN,FUN(M))
43  IF (FUN(M).GE.YMN) GO TO 47
      IF (ABS(FUN(M)-YMN).LE.AMAX1(EP,EP*YMN)) GO TO 47
C  GIVE IT ANOTHER TRY UNLESS LIMIT ON TRIALS REACHED.
44  YMN = FUN(M)
      FUN(1) = FUN(M)
C
      DO 45 I=1,NV
      CEN(I) = V(I,M)
      SUM(I) = V(I,M)
45  V(I,1) = V(I,M)
C
      DO 46 I=1,NVT
46  XS(I) = V(I,M)
C
      IF (IER.LT.3) GO TO 6
47  IF (NPR.LE.0) GO TO 48
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,V(1,M),-1)
      WRITE (6,56) FUN(M)
48  RETURN
C
49  FORMAT (50H0INDEX AND DIRECTION OF OUTLYING
      1VARIABLE AT STARTI5)
50  FORMAT (50H0IMPLICIT CONSTRAINT VIOLATED AT START.
      1DEAD END.)
51  FORMAT ('0CANNOT FIND FEASIBLE',I4,'TH VERTEX OR
      1CENTROID AT START.')
52  FORMAT (10H0AT TRIAL I4,54H CANNOT FIND FEASIBLE

```

```

1VERTEX WHICH IS NO
2LONGER WORST,I4,15X,'RESTART FROM BEST VERTEX.')
53 FORMAT (40HOFUNCTION HAS BEEN ALMOST UNCHANGED
1FOR I5,7H TRIALS)
54 FORMAT (27HOLIMIT ON TRIALS EXCEEDED. )
55 FORMAT ('OBEST VERTEX IS NO.',I3,' OLD MIN WAS ',
1E15.7, ' NEW MIN IS ',E15.7)
56 FORMAT ('OMIN OBJECTIVE FUNCTION IS ',E15.7)
END
SUBROUTINE FBV (K,FUN,M)
DIMENSION FUN(50)
M = 1
C
DO 1 I=2,K
IF (FUN(M).LE.FUN(I)) GO TO 1
M = I
1 CONTINUE
C
RETURN
END
SUBROUTINE BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FN,C,IK)
DIMENSION V(50,50), FN(50), C(25)
WRITE (6,4) NT,NPT,NFE,NCE
C
DO 1 I=1,K
WRITE (6,5) FN(I),(V(J,I),J=1,NV)
IF (NVT.LE.NV) GO TO 1
NVP = NV+1
WRITE (6,6) (V(J,I),J=NVP,NVT)
1 CONTINUE
C
IF (IK.NE.0) GO TO 2
C
WRITE (6,7) (C(I),I=1,NV)
RETURN

```

```

2 IF (IK.GE.0) GO TO 3
  WRITE (6,8) (C(I),I=1,NV)
  RETURN
3 WRITE (6,9) IK,(C(I),I=1,NV)
  RETURN

```

C

```

4 FORMAT ('ONO. TOTAL TRIALS = ',I5,4X,'NO. FEASIBLE
1TRIALS = ',
2I5,4X,'NO. FUNCTION EVALUATIONS = ',I5,4X,'NO.
3CONSTRAINT EVALUATIONS
4= ',I5/'0      FUNCTION VALUE',6X,'INDEPENDENT
5VARIABLES/DEPENDENT
6OR IMPLICIT CONSTRAINTS')
5 FORMAT (1H ,E18.7,2X,7E14.7/(21X,7E14.7))
6 FORMAT (21X,7E14.7)
7 FORMAT (10HOCENTROID 11X,7E14.7/(21X,7E14.7))
8 FORMAT ('O  BEST VERTEX',7X,7E14.7/(21X,7E14.7))
9 FORMAT ('OCENTROID LESS VX',I2,2X,7E14.7/(21X,7E14.7))
END

  FUNCTION FE(X)
    DIMENSION X(3)
    COMMON TDIFF
    CALL PLANT(X)
    FE=TDIFF
    RETURN
  END

  FUNCTION KE(X)
    DIMENSION X(3)
    KE=0
    RETURN
  END

```

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